Methods for the assessment of low-frequency noise from mining activities in the Netherlands

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Publiekssamenvatting

Probleemstelling

Dit rapport betreft een literatuuronderzoek naar laagfrequent geluid (LFG) van mijnbouwactiviteiten dat is uitgevoerd in het kader van het Kennisprogramma Effecten Mijnbouw (KEM). In Nederland neemt het aantal klachten over hinder door LFG toe. Een deel van deze klachten wordt toegeschreven aan LFG afkomstig van mijnbouwactiviteiten. Een effectieve methode voor de beoordeling van LFG uit dergelijke bronnen ontbreekt nog. In dit onderzoek is gefocust op mijnbouwactiviteiten in Nederland, gerelateerd aan de winning, verwerking, transport en opslag van olie, gas, zout en aardwarmte.

Multidisciplinaire aanpak

In dit rapport is kennis bijeengebracht uit verschillende wetenschappelijke disciplines, waaronder akoestiek, werktuigbouwkunde, epidemiologie en psychologie. Deze kennis is verkregen met literatuuronderzoek binnen de wetenschappelijke literatuur, en met interviews met domeinexperts uit binnen- en buitenland. De multidisciplinaire benadering die is gebruikt, heeft gezorgd voor meerdere perspectieven op dit onderwerp. Deze aanpak is over het algemeen ongebruikelijk in het onderzoek naar LFG.

Brede laagfrequente geluidsband

In dit rapport is een brede laagfrequente geluidsband bekeken, die zowel infrasoon geluid (onhoorbaar geluid met frequenties minder dan 20 Hz) als geluid met frequenties tot 200 Hz omvat. Hierbij kan worden opgemerkt dat verschillende definities van LFG worden gehanteerd, zowel internationaal als binnen Nederland zelf.

Conclusies en aanbevelingen

De verschillende aspecten van deze disciplines die verband houden met LFG worden besproken en samengevat in de volgende deelhoofdstukken:

1. Meten en berekenen van LFG
2. Opwekking van LFG door bronnen die relevant zijn voor de mijnbouw
3. Perceptie van LFG en gezondheidseffecten

Op basis van de resultaten van dit onderzoek zijn aanbevelingen gedaan met als doel het definiëren van procedures voor het beoordelen van LFG, afkomstig van mijnbouwactiviteiten.

Uit dit rapport volgt dat de beoordeling van LFG uit mijnbouwinstallaties een groot aantal variabelen en onbekenden omvat, waardoor een eenvoudige beoordeling van LFG-uitstraling niet altijd mogelijk is. Daarnaast volgt uit dit literatuuronderzoek dat veel kennis nog niet is gecentraliseerd, en dat vervolgonderzoek voor LFG vaak nodig is. Dit betreft onder andere de algemene karakterisatie van het geluidsveld, verder onderzoek naar geschikte meetstandaarden, casestudies naar LFG-uitstraling nabij mijnbouwinstallaties evenals onderzoek om dosis-effect relaties af te kunnen leiden. Hierbij is het belangrijk dat nieuwe onderzoeken zo mogelijk in samenhang worden gecoördineerd en besproken.

Acknowledgements

This research has been carried out in the framework of the Knowledge Program Effects of Mining[2] (KEM), on request by the Dutch State Supervision of the Mines (SSM).

We would like to thank all experts that have contributed to the interviews that have been carried out as part of the research. The list of interviewees is included as Appendix to this report. The interviews have helped in the definition of the scope of the work and have directed the literature review.

In addition, we would like to express our gratefulness for the helpful reviews that have contributed significantly to the final report. The reviews were provided by Abhishek Sahai (RIVM), Irene van Kamp (RIVM), Norm Broner (Broner Consulting Pty Ltd), Gijsjan van Blokland, and Roger Waxler (National Center for Physical Acoustics at the University of Mississippi, USA).

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[2] See project website https://kemprogramma.nl for more information regarding the scope

Abstract

According to the World Health Organisation (WHO), noise ranks among the environmental stressors with the highest impact on public health. The attribution of symptoms to low frequency noise (LFN) is increasing. In the Netherlands, numbers of LFN-related complaints are rising and several of those have been attributed to the mining industry. However, an effective methodology for the assessment of LFN from such sources is not yet available. Within this project, we investigate LFN from mining activities in the Netherlands, focusing on the extraction, processing, transportation and storage of oil, gas, salt, and geothermal heat. Through a literature review and interviews with domain experts, methodologies have been derived with regards to 1) the prediction of LFN generation at the source, 2) observational techniques and 3) potential impacts on health. A broad low-frequency band is considered, spanning from the often-discarded infrasonic frequencies, to up to 200 Hz. Based on this study's results, recommendations are given for establishing a standard procedure to assess LFN produced by mining activities.

1 Introduction

1.1 Background

The objective of this study is the assessment of low frequency noise (LFN) from mining activities, by gas production, transport, and storage activities, as well as activities related to the production of geothermal energy and salt. According to the World Health Organisation (WHO), noise ranks among the environmental stressors with the highest impact on public health (WHO, 2011). It is therefore important to regularly monitor for possible effects on health. The rapid expansion of infrastructure has increased the attribution of symptoms to LFN and public concern. In the Netherlands, numbers of LFN-related complaints are rising and several of those have been attributed to the mining industry. An example of one the cases is the underground gas storage facility near Grijpskerk. However, earlier investigations that have been conducted (OGD, 2016; Sijl et al., 2011) have led to different conclusions.

A systematic evaluation of observational studies suggests an association between exposure to LFN and self-reports of annoyance and various symptoms in the population (Baliatsas et al., 2016). However, results should be interpreted with caution due to the small number of existing studies. Moreover, it is found that not all LFN complaints can be associated with physical sound sources. This illustrates the complexity of LFN assessments (Van den Berg, 2009).

As vibrations in the ground and the atmosphere couple well at low frequencies, these are to be studied jointly (Averbuch et al., 2020; Sylvander et al., 2007). Infrasound is typically defined as sound with frequencies below 20 Hz (Leventhall, 2009). The definition of the LFN frequency range varies strongly by country, but generally falls between 20-250 Hz. In the Netherlands frequencies between 20-100/125 Hz are generally considered as LFN (White et al., 2020). In the continuation of this work, the term *LFN* comprises both the inaudible (infrasonic) and audible low-frequency bands.

It should be noted that infrasound can be perceived, albeit at levels that exceed the audibility threshold. However, background levels that are typical of urban and rural landscapes are below this threshold and therefore are not perceivable. While the response of the body (e.g., chest resonances) has been considered in the past, no evidence of extra sensitivity beyond the ear has been found for humans (Leventhall, 2009). A significant role of the body in the perception of LFN is considered for other species (Zeyl et al., 2020).

Noise within the LFN spectrum comprises a common, everyday-life environmental exposure, produced by natural sources (sea waves, severe weather, earthquakes; (Campus & Christie, 2009)) as well as by man-made sources (industrial installations, domestic appliances, transportation, and induced earthquakes; see (Berglund et al., 1996)). Natural sources of LFN are typically found below frequencies of 1-2 Hz. Anthropogenic sources typically produce higher frequency signals, and the spectra are often characterized by characteristic tones / harmonics that can typically be linked to the geometrical properties of the sources. While the latter category is of interest for this study, it is important to consider anthropogenic sources in the presence of natural infrasonic sources in the transitional frequency band of 1-10 Hz.

1.2 Scope of the research

In the framework of the Knowledge Program Effects of Mining[3] (KEM) a review study of LFN from mining activities was initiated on request by the Dutch State Supervision of the Mines (SSM).

The scope of the research has been defined to include the following topics:

1. An inventory and characterisation of generated LFN from processing facilities including equipment and the flow of gas and liquids through pipeline systems, as well as from induced earthquakes.
2. Methods on how to use technical observational systems as well as observation by citizens or models for proper assessments of current or future LFN generation and exposure to be expected.
3. An overview of potential impacts of LFN on the environment and people, and references to any safety norms.

The results of this study are intended for use:

1. by the Ministry of Economic Affairs and Climate Policy, to decide upon the need for a specific approach and norms to infrasound/LFN, or adaptation of current approaches.
2. by SSM, to advise the Ministry, responsible for LFN safety/health issues, to address mining activities and guideline for best practice.
3. by operators and gas, geothermal energy, and salt transport/processing companies to comment and use.
4. by the public and scientific communities in the Netherlands.

In our study, we review knowledge from various scientific disciplines, which include acoustics, mechanical engineering, and perception. The various aspects of these disciplines are described separately as well as in conjunction.

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3 See project website https://kemprogramma.nl for more information regarding the scope

1.3 Methodology

We have performed a literature review and have interviewed Dutch and international experts on these three topics, which have been organized within separate work packages (WPs) 1, 2 and 3. The various WPs and associated research questions are summarized in the table below:

Work Package	Theme	Research question	Chapter
WP2	LFN Monitoring	Which monitoring and/or measuring techniques and networks are available internationally and in The Netherlands, and could/should be used to cost-effectively monitor or measure LFN generated by mining activities?	2
WP1	Sound generation and source models	Which assessment methods exist and could/should be used to predict the generation of LFN from mining activities, specifically (1) man-induced earthquakes, (2) gas transport and processing facilities for gas, (3) geothermal energy and salt facilities, such as rotating equipment (compressors, turbines, pumps) and furnaces?	3
WP3	Perception	What norms exist internationally for the level of exposure of people to LFN, comparable to audible sound?	4

Table 1 Overall study design and associated research questions

For each work package, experts from a representative selection of organizations (academia, research institutes, engineering firms, instrument manufacturers, suppliers of measuring instruments and machinery for mining activities) have been interviewed to get a broad perspective. The interviews have been used to help direct the literature review, in order to base this review study on peer-reviewed research.

1.3.1 WP1: Emission of LFN

Insight is needed on possible sources of LFN to efficiently tackle LFN related problems. It should be remarked that this holds if one of these sources is actual source of the LFN being investigated. Sometimes, the source is not known but the problem still needs to be addressed. This is discussed as part of WP3. The goal of WP1 is to collect information on typical sources of LFN within the mining industry. The questions presented below served as a guideline when speaking with experts in the field. Besides expert consultants and academic researchers, interviews were held with people from within the mining industry itself as well as with building contractors and equipment manufacturers.

WP1 questionnaire:

1. **Equipment**
    a. Type of equipment used in the mining industry
        i. Typical models and suppliers
        ii. Typical mounting / foundation / setup
    b. Relevance of equipment for emission of LFN and/or vibrations
    c. Generation processes of LFN

2. **Prevention and prediction methods**
    a. Prediction methods used prior to commissioning
    b. Norms used as a reference
    c. Standard measures taken to prevent LFN / vibrations

3. **Measures**
    a. Measures used or known to be able to solve LFN emission…
        i. …at the source
            1. Technical
            2. Organizational
        ii. …in the sound path
        iii. …at the dwelling

Based on literature and interviews, information on generation processes leading to LFN emission from mining equipment is collected. In addition, an overview is created on prediction methods, rules of thumb for prevention- and possible measures to mitigate LFN, as well as measuring techniques for characterisation of noise and vibrations at the source.

A list of interviewees is included as Appendix 7.1

1.3.2 WP2: Monitoring of LFN

In the monitoring of LFN sources, it is convenient to separate the following:

1. The acoustical and vibrational spectrum of the LFN source; and
2. The environment (subsurface and atmosphere) as transfer function, describing the propagation of sound and vibrations from the source to a receiver location; and
3. The measurement conditions near the receiver.

For example, consider that the enhanced transmission of low frequencies from a particular source (1) into dwellings can be attributed a combination of (varying) environmental propagation conditions (2) as well as the efficient coupling into houses at these frequencies (3). This work package involves a brief review of the topics relevant to points 2 and 3. Characteristics of the LFN source are discussed as part of WP1.

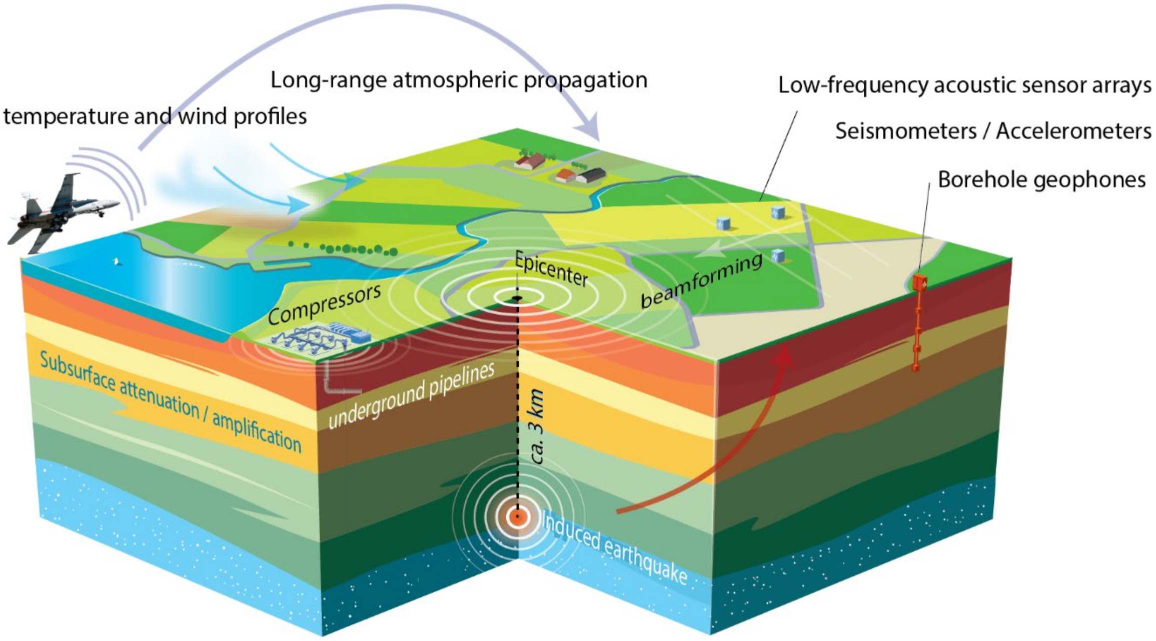

Figure 1 Schematic of example LFN monitoring techniques that are of interest for this work package, including accelerometers and low-frequency sound arrays. Such techniques can be used to identify concurrent LFN sources that may or may not be related to the mining industry but lead to similar perceptions in the near field (e.g., sonic boom and induced earthquakes).

For the interviews, a questionnaire was prepared, focusing on relevant themes in the monitoring of LFN (See Figure 1).

WP2 questionnaire

1. **Technical properties**
    a. Technical equipment that is used in the measurement
    b. Calibration techniques for the used devices
    c. Choice of parameters to characterize the LFN field (pressure, vibration)

2. **Design of measurement setup**
    a. Continuous 24/7 operations or measurement campaigns
    b. Filtering of (in)coherent noise from data (e.g., wind noise)

3. **Measurement conditions and role of the environment**
    a. Measuring inside vs. outside dwellings
    b. Role of the environment:
        i. Subsurface geology for the enhancement / attenuation of vibrations
        ii. Influence of the atmosphere on the measured sound levels
            1. Wind noise
            2. Long-range propagation conditions
    c. Reference measurements and background noise models

4. **Processing methodology**
    a. Routine time- and frequency-domain analysis
    b. Processing workflow: time-domain and frequency-domain parameters
    c. Sound level quantifiers
    d. Signal detection, association, and localization
    e. Array processing

A list of interviewees is included as Appendix 7.2.

1.3.3 WP3: Perception of LFN

In Work Package 3, the perception and health effects of LFN are studied. Additionally, it is investigated whether norms and legislation of regulation on LFN exposure exist internationally. The questionnaire has focused on the following themes:

WP3 questionnaire:

1. **Complaints**
    a. Typical frequency range and appearance (noise/vibration/modulation)
    b. Physical, psychological, and medical aspects.
    c. Routing and authorities involved.

2. **Assessment and regulations**
    a. Norms, guidelines, and regulations
    b. Methods for measurement and monitoring
    c. Prediction methods

3. **Sources and measures**
    a. Relevant sources of LFN inside and outside mining
    b. Relevance of mining in LFN complaints
    c. Successful measures to tackle LFN problems, including:
        i. source & receiver
        ii. technical & process & psychological

4. **Future expectations**
    a. Expected development of LFN complaints in time
    b. Reasons, including:
        i. Changing awareness, attitude, or sensitivity
        ii. Changing hardware (e.g., due to energy transition or noise abatement)
    c. Suggestions to respond to potential changes.

A list of interviewees is included as Appendix 7.3

1.4 Outline of the report

The remainder of this report is organized as follows. Chapter 2 provides a review of the physical aspects that are relevant in the monitoring and simulation of LFN. Chapter 3 provides a description of LFN sources that have been identified to be relevant for LFN for Dutch mining activities. Chapter 4 discusses topics relevant to the perception of LFN, with a focus on the situation in The Netherlands. Each chapter includes a discussion and summary of key points.

2 Monitoring and simulating LFN

2.1 Introduction to elastic waves and LFN

Sound, or acoustic waves are elastic waves that disturb the medium locally when propagating from the source with the speed of sound (approximately 340 m/s at 20°C in air). As an acoustic wave passes by, the medium oscillates, becoming compressed or rarefied. The waves are called elastic waves because the medium is restored to its original state after the perturbation has propagated away. Acoustic waves are longitudinal waves, for which the direction of particle displacement is parallel to the wave direction (Pierce, 2019). In seismology, acoustic waves are referred to as P-waves. Shear waves or S-waves, constitute another class of elastic (body) waves and can only exist in solid media. These waves are characterized by transverse wave motion. The particle motion of S-waves is polarized in the vertical and horizontal plane, leading to SV- and SH-waves. Along medium interfaces, such as the Earth’s surface, elastic waves may propagate as Rayleigh (coupled P-SV) and Love (SH) surface waves. Surface waves propagate slower than the body waves but generally have higher amplitudes because the geometrical spreading, i.e., the area that the wave energy covers is much smaller (Stein & Wysession, 2009). The interface conditions (continuity of pressure and continuity of displacement normal to the interface) between neighboring media allow for the energy transfer of P- and SV-wave motion. Such seismoacoustic conversion occurs between the subsurface and the atmosphere (Averbuch et al., 2020; Sylvander et al., 2007) and is discussed more in detail in Section 3.5.

The wavefield at any given position can be described by the perturbations in pressure (unit is pascal or Pa) or particle velocity (unit is m/s). The magnitude of the particle velocity is in the order of mm/s and is much smaller than the propagation speed. Seismic waves are typically measured using three-component geophones/accelerometers that respectively measure the particle velocity/acceleration in the vertical and two horizontal directions. Sound in the atmosphere is typically measured using pressure transducers such as condenser microphones, although sensors have been developed for the measurement of particle motion in air (de Bree, 1997). The sound intensity quantifies the acoustic energy as well as its directivity and is calculated as the product of sound pressure and particle velocity (Pierce, 2019). The intensity decreases with distance from the source, with most rapid decrease in the nearfield.

The sound frequency quantifies the number of the acoustic oscillations per second (unit is Hertz). Fourier analysis techniques can be used to decompose the acoustic wave into a frequency spectrum, by representing the complex waveform as a summation of simple sinusoids. This is akin to when light is split by a prism. Infrasound is typically defined as sound with frequencies below 20 Hz (Leventhall, 2009). Frequencies between 20 Hz and 20 kHz are generally audible. There is still debate on the definition of LFN as several countries have defined LFN in their own manner. It generally falls between 20-250 Hz (White et al., 2020). It should be noted that sounds in the infrasonic domain can - in fact - be perceived, albeit at levels that exceed the audibility threshold. LFN can be produced by large air volume displacements, either from natural or anthropogenic sources. A large variety of sources have been identified and reported in the literature (Campus & Christie, 2009) that originate from natural (sea waves, severe weather and lightning, earthquakes, and meteor explosions) as well as by man-made sources (Berglund et al., 1996), such as wind turbines, industrial installations, bridges, domestic appliances, transportation, or induced earthquakes. Radiation at low frequencies can be enhanced when resonances occur due to the geometry of the source and/or if the source if connected to large surface areas which are efficient in the radiation of sound. LFN sources are further discussed in Chapter 3.

2.2 Measurement Techniques

2.2.1 Sensor systems and sensor networks

For the measurement of any quantity, it is essential that the (frequency-dependent) system response is well characterized and stable over the measurement period. Ideally, the system response is flat over the frequency band of interest (Figure 2). The full system response includes (1) characteristics of the wind screens, (2) the analog sensor, (3) any analog filter systems as well as (4) the analog-to-digital (A/D) conversion (Havelock & Kuwano, 2009).

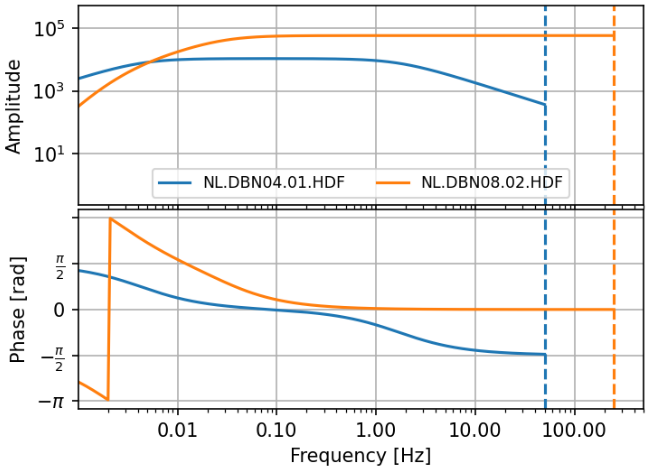

Figure 2 Sensor responses of two different LFN systems. The orange curves correspond to a system with a Nyquist frequency at 250 Hz (i.e., with a sampling frequency of 500 Hz), and a flat response over the full LFN band up to 200 Hz. The blue curves correspond to an infrasound sensor with a Nyquist frequency at 50 Hz. The sensor has a flat response in the lower infrasound band (0.01-2 Hz). The high-frequency cut-off occurs because of the applied wind noise filters.

In modern A/D systems, digitization of the signal occurs by means of massive oversampling and averaging until the desired sampling frequency is reached. The maximum resolvable frequency, or Nyquist frequency, corresponds to half the sampling frequency. It is good practice to discard frequencies greater than 80% of the Nyquist frequency to avoid effects of the digital filters that are part of the A/D-converter (Sleeman et al., 2006).

A combination of various sensor types is needed to fully capture sound and vibrations relevant to LFN source in a broad frequency band, ranging from infrasonic frequencies up to 200 Hz. Recently, pressure transducers have become available that have a flat frequency response over a broad frequency range ranging from 0.01 up to 200 Hz (Merchant, 2015). A seismoacoustic measurement is needed if one is to study vibrations in the subsurface as well as those in the air. The former is typically measured with a geophone or accelerometer, the latter with a pressure transducer. For audible frequencies, condenser microphones are widely used (Havelock & Kuwano, 2009). For the measurement of atmospheric infrasound, so-called micro-barometers have been designed (Mentink & Evers, 2011).

Acoustic particle motion detectors, in particular hot-wire anemometers, also have a very long history (Comte-Bellot, 1976). A relatively recent version of such a device is the Microflown (de Bree, 1997). This device is a directional microphone which measures acoustic particle velocity instead of acoustic pressure and allows for wavefront directivity measurements (Zon et al., 2009). The instrument response of the Microflown has been characterized over a band spanning from infrasound, up to audio frequencies of 20 kHz. The instrument is characterized by a low self-noise. Measurements are strongly influenced by the wind, which implies the need for wind screens. The combination of a particle velocity and a pressure transducer allows for acoustic intensity measurements. Sound intensity probes combine two pressure sensors (*p-p* method), or a pressure and particle velocity sensor (*p-u* method) (Havelock & Kuwano, 2009). This application is particularly interesting near the source, where source directivity plays a larger role.

Sound level meters are widely used for general noise studies and consist typically of a condenser microphone, a digitizer as well as built-in software for computing standardized sound level quantities. The international standard for sound level meters (IEC 61672-1) defines frequency weighting schemes (as discussed in Section 2.3.1) as well as two separate accuracy classes (Havelock & Kuwano, 2009). Class 1 has the highest accuracy, i.e., within 2 dB at the reference frequency of 1 kHz. Note that typical sound level meters use microphones that are not optimal for infrasonic frequencies.

2.2.2 Low-cost sensors

Typical sensor systems that are in use for the reliable measurement of LFN are relatively expensive, which can be an impediment for larger scale deployment for the monitoring of LFN, for example nationwide. Technical advances in low-cost miniature sensor technology, such as Microelectromechanical systems (MEMS) sensor technology, have led to an increased interest in the application of such sensors to supplement existing networks. Even though the quality is typically compromised when compared to high-fidelity systems, low-cost systems also have advantages such as reduced weight, size, and power. These benefits allow for innovative deployment strategies. Recent studies have applied MEMS technology in a mobile geophysical measurement platform (O. den Ouden et al., 2020), and in a LFN monitoring campaign of geothermally induced earthquakes (Lamb et al., 2021).

One of the main applications of MEMS sensors are personal devices, such as smartphones. These devices typically contain multiple MEMS sensors. A method has recently been presented for the characterization of the amplitude response of both built-in smartphone microphones as a smartphone extension condenser microphone, relative to calibrated high-fidelity equipment in a broad frequency range spanning from 0.5 to 2000 Hz (Asmar Toro, 2019). By characterizing the response, it may become possible to estimate sound pressure levels at frequencies of interest for LFN studies. All tested device types show reduced sensitivity below 31.5 Hz as well as an increased self-noise level at the lower frequencies.

The prevalence of smartphone devices and the ability to use the sensors in a crowdsourcing context has been helpful in various applications, such as the detection of moderate earthquakes (Kong et al., 2016).

2.2.3 Calibration

Confidence in the measurement of the sound pressure level of LFN sources is crucial to understand our environment and establish legal acceptance levels of LFN. The primary reference method routinely used in the National Metrology Institutes for sound pressure calibration is the pressure reciprocity method, applied at frequencies up to 25 kHz and, recently down to infrasonic frequencies. While infrasound is a well-established scientific discipline, primary and secondary calibration standards are yet to be standardized at infrasonic frequencies, allowing for traceability and repeatability of such measurements. The Infra-AUV project[4] on metrology for low-frequency sound and vibration (Infra-AUV, 2020) will focus on this topic.

2.3 Processing LFN data

Due to the relatively low rates of attenuation and long propagation distances, the acoustic wavefield at low frequencies is a mixture of sounds that originate from a diversity of sources that radiate sound in various frequency bands. In addition to acoustic waves, the pressure field also consists of pressure fluctuations that originate from intrinsic turbulence and the interaction of the wind with the sensors (Raspet et al., 2018). These pressure fluctuations are often referred to as 'wind noise' (also see Section 2.4.2). Because of these aspects, it can be difficult to identify individual sources of LFN without the application of specialized techniques. Typically, a network of sensors and digital processing techniques are needed to detect the sound waves, identify the source location, and characterize the source.

2.3.1 Time- and frequency domain methods

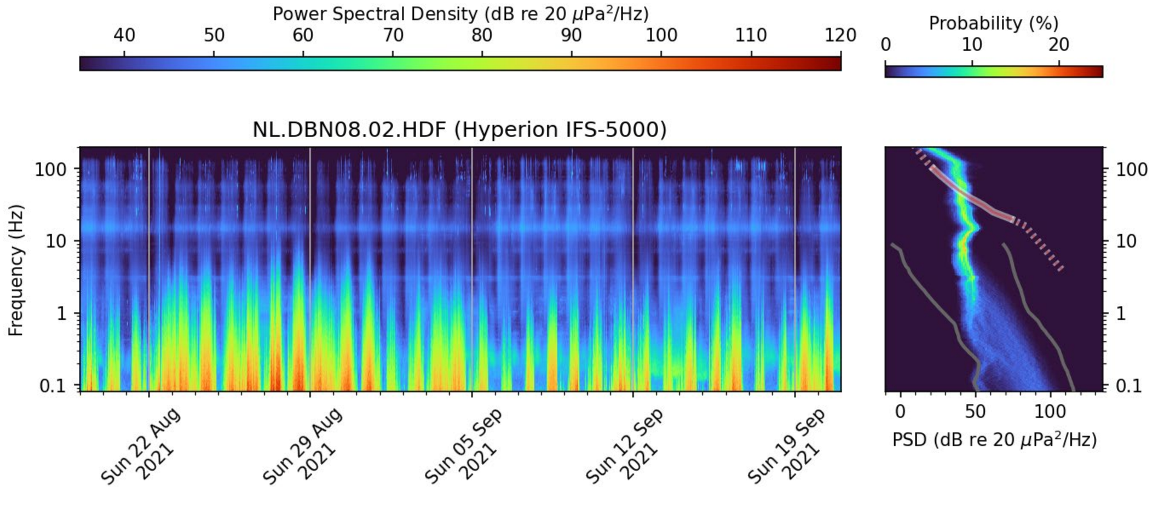

Figure 3 Spectrogram of the background LFN field at frequencies between 0.1-200 Hz recorded at KNMI, De Bilt, The Netherlands. The site is located near several major Dutch highways. The frame on the right shows the associated Probabilistic Power Spectral Density (PPSD), the NSG audibility threshold (NSG, 1999; red line) *and the infrasonic background noise models* (Brown et al., 2014; gray lines). *Several man-made LFN sources can be identified across the frequency band above 1 Hz as horizontally banded features, which increase in power during weekdays. The influence of wind noise (vertical features) significantly masks the field below 5 Hz, during the day. The PPSD shows the characteristics of the background noise profile. It is expected that sound levels that exceed the NSG threshold can be perceived.*

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[4] Project website: https://www.ptb.de/empir2020/infra-auv/home/

Most processing techniques that are in use for the processing of LFN fall in the two main categories of time-domain and frequency-domain techniques with spectrogram class methods as a hybrid time-frequency approach (Figure 3). Each class has advantages and drawbacks, and it is often useful to consider multiple approaches in the analysis of acoustic data. The ability to resolve spectral features depends on the characteristics of the full system response (as discussed in Section 2.2). The spectral resolution itself depends on the length of analyzed timeframe.

The processing resolution is very dependent on the required application. By engineering standards, (third) octave bands are often accurate enough. For research (such as transfer functions, Section 2.5) it is sometimes useful to perform more detailed narrowband analyses to be able to measure specific tonal components (Havelock & Kuwano, 2009).

While the sound pressure is typically measured in terms of pascal, reported measurements are often expressed using decibel scale (dB), relative to the hearing threshold of 20 micropascal, defined at 1 kHz. The logarithmic dB scale is useful for the processing of acoustic data and matches the sensitivity of the human ear to sound loudness (unit is *phon*). It is common practice to measure and assess LFN without weighting filters that correct for the sensitivity of the human ear to sound loudness (linear or Z-weighting). The A-filter (dB(A)) corresponds to the inverse of the 40 phon contour and has a half power (-3 dB) point at 500 Hz. The relationship between the dB value and loudness is much steeper at low frequencies, because of the reduced sensitivity of the ear. The C-filter (dB(C)) is another commonly used filter in the measurement of LFN for which the half power point is at 31.5 Hz (Figure 4). The A-, C- and Z-filters have been defined within the international standard for sound level meters (IEC 61672).

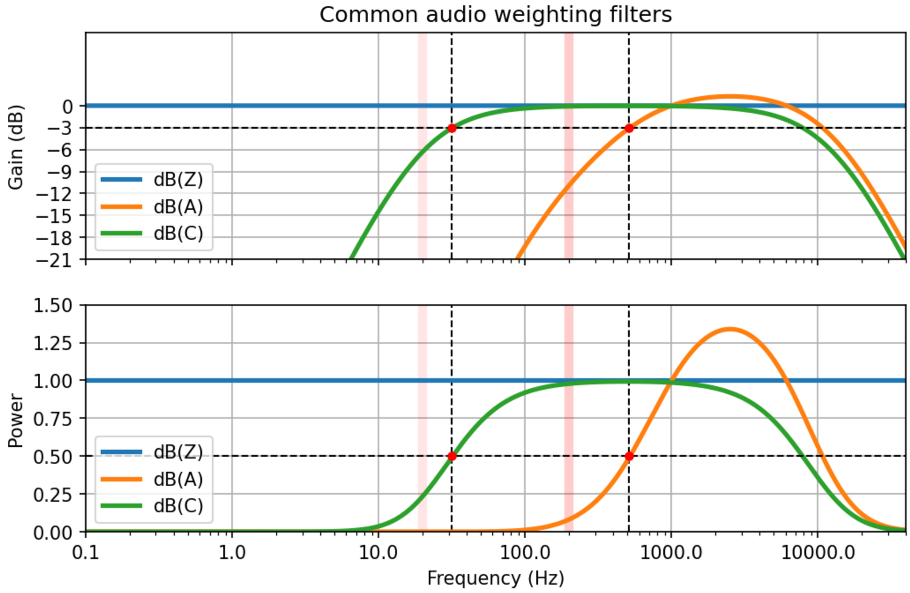


Figure 4 Common audio weighting filters dB(A) and dB(C) relative to the unweighted filter dB(Z). These filters have been defined within the international standard for sound level meters (IEC 61672). The half-power point of the dB(A) and dB(C) filters are found at 500 and 31.5 Hz, respectively. The vertical red curves correspond to 20 and 200 Hz.

When quantifying the sound field, energy averages are typically used in the reporting. These correspond to monoaural measures since phase information, on which binaural measures rely, is omitted. From these energy measures, standard measures have been derived to estimate average noise levels during the day (L_{day}), night (L_{night}) and over an entire day (L_{den}). Such measures average out sudden increases in sound pressure levels that occur under the influence of the environment (Section 2.4). Measures like L_1, L_{10} or L_{max} are available for statistical description of variation. It should be investigated what integration times would be applicable for LFN sources of interest.

2.3.2 Sensor networks

The Netherlands Seismic and Acoustic Network is operated by KNMI and consists of accelerometers, geophones, broadband seismometers, and infrasound sensors (Figure 5). The network is designed for the detection and characterization of seismicity in The Netherlands, the characterization of surface acceleration, and for the detection of infrasound. The data from the network is collected continuously and is made available through online webservices.

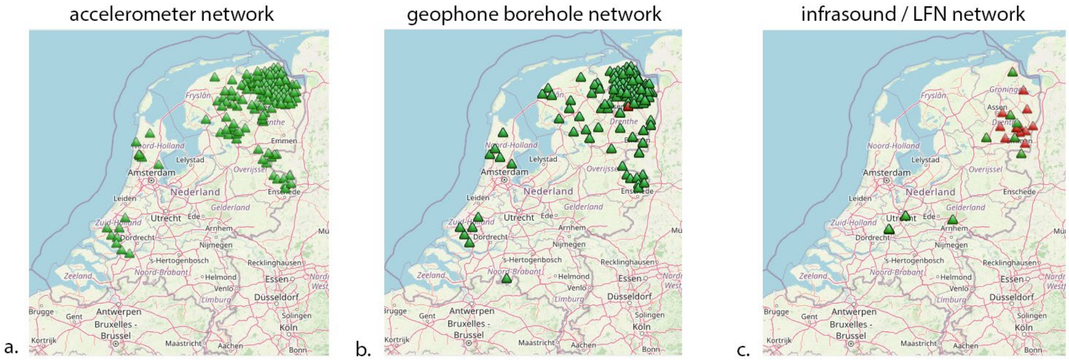


Figure 5 Locations of the (a) accelerometers, (b) geophones and (c) infrasound-LFN arrays networks that are part of the Netherlands Seismic and Acoustic Network (KNMI, 1993)*. An interactive version is available through http://rdsa.knmi.nl/network/NL/. The IRIS webservice http://ds.iris.edu/gmap/ provides an inventory of seismo-acoustic networks worldwide.*

2.3.3 Array processing and directional microphones

The use of arrays is twofold (Läslo G. Evers, 2008):

1. Detection: arrays are used to distinguish acoustic signals of interest from noise (both acoustic and non-acoustic). The sensors are far enough apart so that the noise is decorrelated, whereas the acoustic signal of interest is correlated. A gain in signal-to-noise is achieved, proportional to the square root of the number of array elements.
2. Array processing allows one to estimate the horizontal and vertical incidence angles from where the signal arrived. This information is of primary importance in the localization of sound sources, particularly at longer distances.

Multiple pressure sensors can be placed within the correlation length of an acoustic wavefront, to form an acoustic antenna or array. The array layout determines the response of an array to an incoming wave (Figure 6). The aperture, or largest distance between the array elements, determines the lowest frequency that can be resolved. The number of sensors, as well as the distances and orientations between sensors pairs, determine the degree of spatial aliasing. The directionality of the antenna is described by the shape of the response curve. Omnidirectional response curves have equal sensitivity to all directions (Läslo G. Evers, 2008).

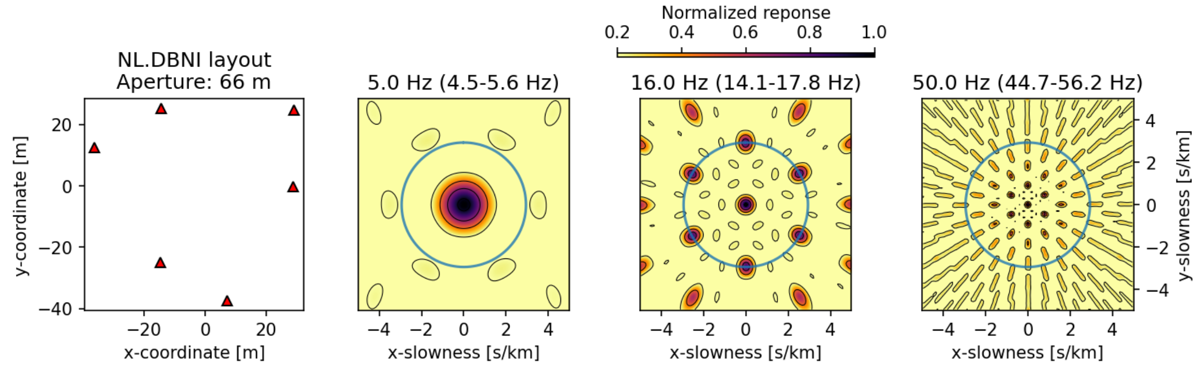


Figure 6 Array response simulations for a six-element, 66 m aperture array (left). A vertically incident plane wave (slowness 0 s/km) is simulated for frequency bands defined around 5, 16 and 50 Hz. The blue circle corresponds to the acoustic speed in air (0.34 km/s). The width of the main lobe corresponds to the resolution. The round shape of the main lobe illustrates the omnidirectional sensitivity of the array. At higher frequencies, spatial aliasing occurs because of the large distance between the elements as is illustrated by the increase in sidelobes. This can be reduced by placing the elements closer together.

Array processing methods can be used to detect coherent sound waves and estimate the directivity. One of the most basic approaches is to determine the time delays between the waveforms recorded on all array elements (Figure 7) and determine the angles of incidence. A detailed review of such methods goes beyond the scope of this report, and the reader is directed to excellent reviews that have appeared in literature (Krim & Viberg, 1996). Applications of high-resolution beamforming techniques demonstrate that acoustic arrays can be used to detect multiple low-frequency sources (den Ouden et al., 2020).

To optimize array performance, it is important in the deployment of array elements that noise levels (e.g., signals that are not of interest) are as low as possible to increase signal correlation between the array elements. This can be achieved by not placing sensors near a busy road of near objects that could lead to turbulence (see Section 2.4.2). There is a trade-off between the accuracy in the direction determination (for which the distance between microphones should be as large as possible) and detectability (for which this distance should be as small as possible). A different approach involves the use of particle motion sensors (de Bree, 1997), which enables the estimation of wavefront directivity at one point in space. Consequently, the mentioned trade-off does not apply to that class of sensors.

2.3.4 Localization

Localization techniques can be divided up into active (e.g., sonar, echo location) and passive localization techniques. Passive techniques are used to identify the location of a sound source based on the sound field it emits and are of relevance for monitoring LFN. The amplitude and directivity of the sound field can typically be exploited in localization. In both cases, one must be aware of the radiation pattern because anisotropic radiation can influence detection both nearby and at longer ranges.

In the close vicinity of the source, it can be feasible to sample the amplitude field at multiple locations to identify the source. As the sound level reduces with range, this provides with a clear strategy to localize the source.

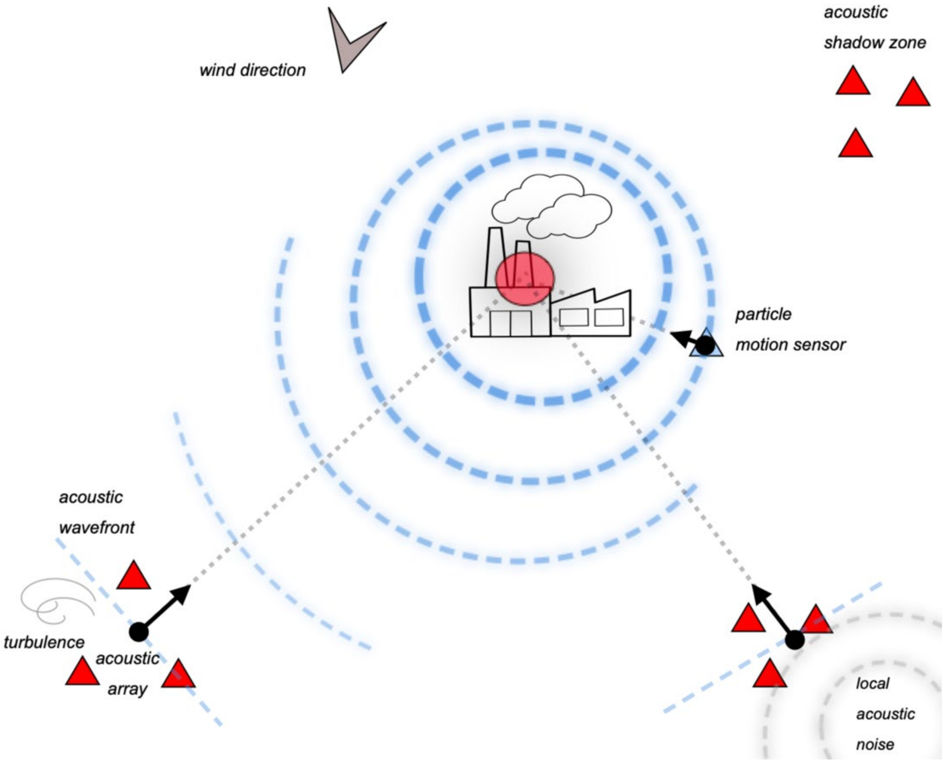


Figure 7 Schematic representation of localization of an acoustic use by cross-bearing localization. In the example, an acoustic source near a factory is localized using observations from a particle motion sensor and an acoustic array. The location of the source is resolved at the intersection of two vectors that are formed using the estimated back azimuths. Note that the sound field is directional due to the presence of presence of a northeasterly wind. Because of this, an acoustic shadow zone exists towards the northeast, where the sound waves are not detected. The detection of the signal of interest can be hampered because of turbulence (left bottom) and/or local acoustic noise (right bottom).

In the far field, one of the most frequently used approaches to localize the source is to triangulate the source by associating observations from multiple microphone arrays. This is referred to as cross-bearing localization and is typically done in the acoustic far field where the wave field is approximately planar. For cross-bearing localization to work, the acoustic source must be detected at a minimum of two array locations, such as depicted in Figure 7. In the case that the source of interest is stationary, it is possible to locate the source using one array by relocating the array multiple times.

2.3.5 Background noise levels

In the assessment of pressure and vibrational spectra, it is important to establish representative background noise models of background spectra to be able to compare the observations to, which can vary strongly as function of location and time. In the seismological, underwater acoustics and infrasound communities, such noise models have been established by compiling spectral databases using data from the respective global observational networks (D. Brown et al., 2014; Wolin & McNamara, 2020). A comparison of LFN measurements in the 0.1-200 Hz in relation to the infrasound background noise models is shown in Figure 3.

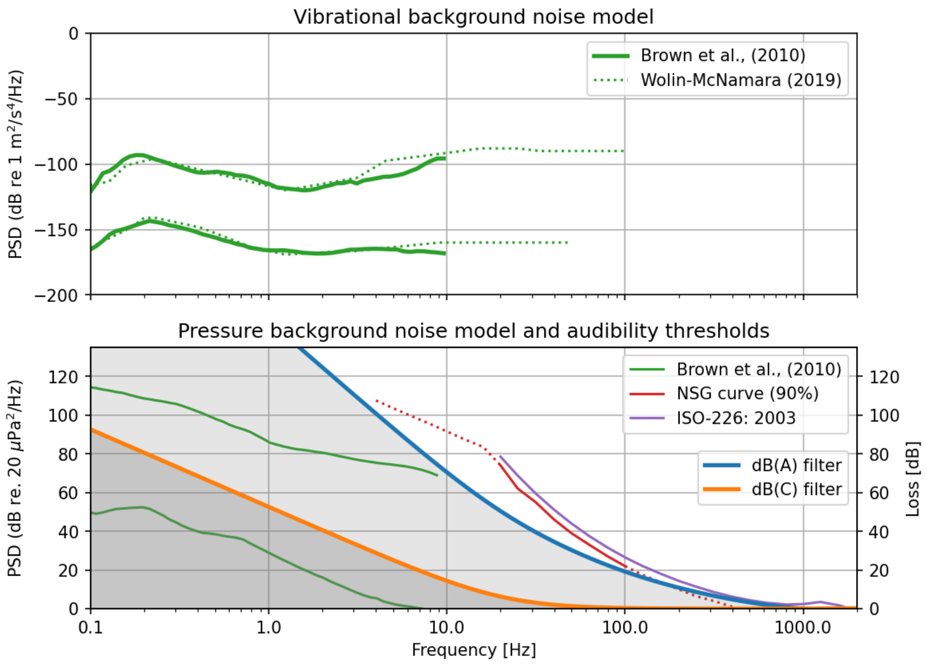


Figure 8 (Top): Low/high noise models of vibrations in the subsurface obtained from seismic observations worldwide showing the 5% and 95% percentiles of all considered background noise levels (Brown et al., 2014; Wolin & McNamara, 2020). (Bottom): Comparison of pressure background noise models with the commonly applied dB(A)/dB(C) filters and audibility thresholds. The shaded areas correspond to the spectral ranges that are filtered out after applying the corresponding filter. Infrasound would be perceivable at levels above the audibility threshold.

The background noise models that are shown in Figure 8 correspond to the 5% and 95% percentile levels of the statistical distribution of considered spectra. A comparison with the dB(A)-filter indeed shows that typical infrasonic levels are not considered (gray shaded area). A fraction of infrasonic energy is considered when dB-C weighting is applied. Comparison with the audibility thresholds that are provided by Nederlandse Stichting Geluidshinder (NSG) (NSG, 1999) as well as the ISO-226: 2003 standard show that infrasound can only be perceived at very high sound pressure levels.

2.4 Influences of the environment

Both the atmosphere and the subsurface can strongly influence the measured LFN field. The detection of LFN depends on the strength of the signal relative to noise levels at a (remote) station. In turn, the signal strength depends on the transmission loss that a signal experiences propagating from source to receiver. The noise levels arise from near-surface wind and the background acoustic noise. Additional near-receiver effects, such as building resonances, can further influence the observations. These are described in Section 2.5.

2.4.1 Propagation of LFN in the atmosphere

In noise studies, it is important to consider the atmospheric parameters that define the acoustic environment. These include temperature, wind, chemical composition, and properties of the subsurface. The wind and temperature distribution in the atmosphere determines along which paths acoustic waves can propagate (Ostashev & Wilson, 2015; Waxler & Assink, 2019). This strongly affects the acoustic transmission loss, which is the combined loss due to geometrical spreading of sound and intrinsic absorption. The atmosphere plays a more significant role for LFN compared to sound at audible frequencies, because the propagation paths are longer, given the low degree of attenuation.

While the wind and temperature fields vary spatiotemporally, several relaxing assumptions can be made in the modelling of acoustic fields:

1. The atmosphere is static during the time of acoustic propagation. Propagation times associated with LFN problems are small enough to warrant this assumption. This assumption is appropriate to capture propagation effects from the mean wind and temperature variations that can be simulated by numerical weather prediction models. However, effects from turbulence and other fine-scale structure that can fluctuate at shorter timescales are then not considered (Drob, 2019; Salomons, 2001). The effects of turbulence can be studied probabilistically by the application of turbulence models (Ostashev & Wilson, 2015).

2. As the atmosphere is predominantly a vertically layered medium, propagation effects are to first order determined by vertical gradients in temperature and wind. Since the vertical wind (order of cm/s) is significantly smaller than the horizontal wind (order of m/s), the effects of the former can be neglected. For propagation distances that are relevant to typical LFN problems (order of kilometers), the effects of lateral variations in temperature and wind are in some cases small enough to justify neglecting these horizontal gradients.

A consequence of these assumptions is that the relevant atmospheric fields that vary in space and time (4D) can typically be reduced to a 1D profiles varying in the vertical dimension for a first-order analysis. This greatly simplifies analysis and reduces computation time, typical of more elaborate propagation models. In what follows, we will consider the effects of vertical temperature and wind gradients (Figure 9).

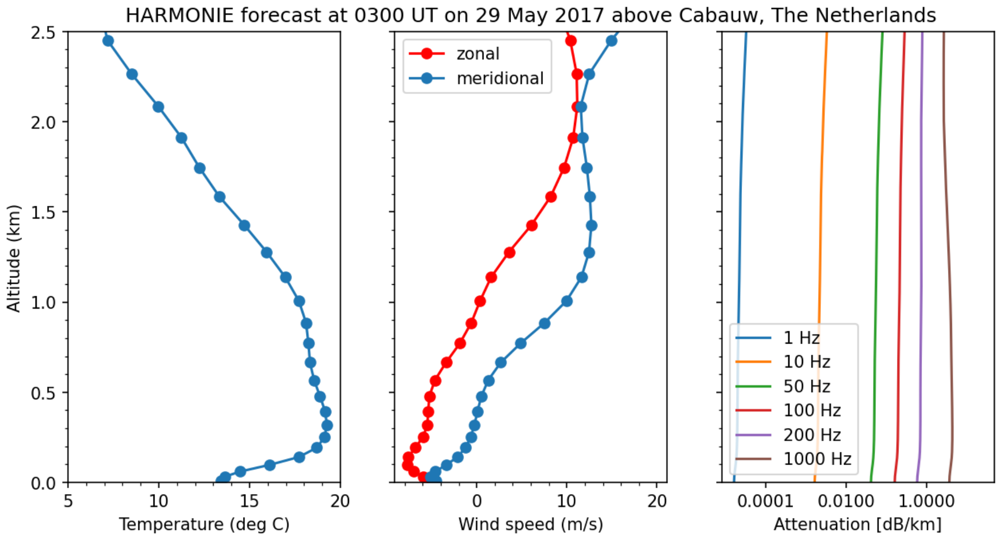


Figure 9 Example forecast for 29 May 2017 at 0300 UTC above Cabauw, The Netherlands showing vertical profiles of temperature and horizontal wind as well as the attenuation model (Sutherland & Bass, 2004) *for various frequencies. A shallow temperature inversion has developed between the ground and ~200 meters altitude.*

The effects of temperature and wind are typically combined in an effective sound speed, which is appropriate for the simulation of (near-)horizontal acoustical propagation paths (Ostashev & Wilson, 2015; Waxler & Assink, 2019). The effective sound speed as function of altitude z is given as: $c_{eff}(z) \cong 20\sqrt{T(z)} + \vec{v}(z) \cdot \hat{n}$, where $T(z)$ is the temperature, $\vec{v}(z)$ is the horizontal wind vector and $\hat{n}$ is the direction of propagation. c_{eff} profiles are useful to interpret propagation conditions. From the perspective of a receiver, they can help to understand from which direction sound can efficiently propagate (Figure 10).

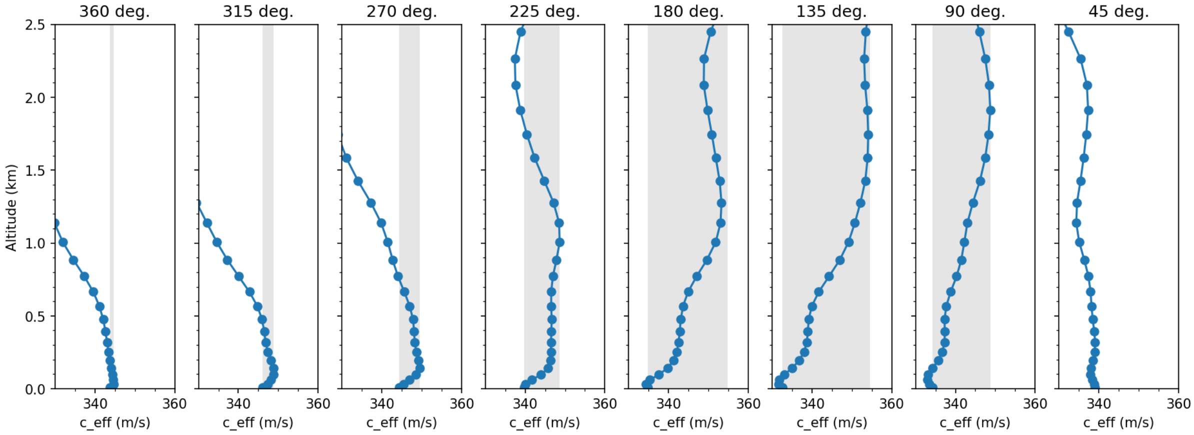


Figure 10 Sound propagation conditions from the perspective of a receiver, for different arrival directions. The effective sound speed profiles are derived from the profiles shown in Figure 9. The area marked in gray shows the 'atmospheric bandwidth' that sound waves can 'use' to propagate. In this example, sound can propagate efficiently from a southeasterly direction (135 degrees from the North), which is consistent with the wind direction. The temperature inversion plays a role in the lowermost layer.

Sound can be refracted, reflected, and diffracted by the vertical variations in the effective sound speed. The ground surface also acts as reflector and scatterer of acoustic energy. Refraction due to vertical gradients in temperature and wind plays a key role in LFN propagation. Diffraction of sound occurs on smaller spatial scales due to interaction with turbulence (Ostashev & Wilson, 2015). Turbulence in the atmosphere is generated where wind shear is large, e.g., near the ground or near buildings or trees (Raspet et al., 2019). The effects of the ground surface will be discussed later in this section.

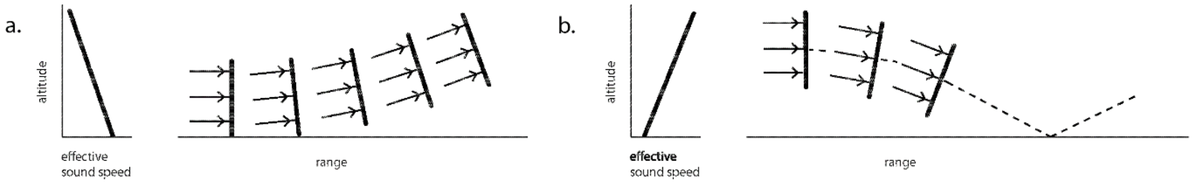


Figure 11 Upward (a) and downward (b) refraction of acoustic waves due to gradients in the effective sound speed.

The geometrical acoustics approximation is widely used to solve wave equations. In this approximation, wavefronts are described by rays and the refraction is described by Snell's law (Pierce, 2019). The index of refraction corresponds to the effective sound speed. It follows that wavefronts bend upward (downward) for negative (positive) gradients in effective sound speed (Figure 11). Realistic temperature and wind profiles typically consist of a combination of these gradient types, which can lead to ground-to-ground propagation paths through the air instead of along the surface. Diffractive effects are not modeled in the geometrical acoustics approximation, and require full-wave models (e.g., Figure 12).

A tailwind situation and/or the presence of a temperature inversion can lead to the formation of sound channels or waveguides between the ground surface and a few hundred meters altitude, wherein acoustic energy propagates efficiently. The presence of acoustic waveguides depends strongly on the prevailing meteorological situation and the time of day (Drob, 2019; Waxler & Assink, 2019). It is well known that the nocturnal boundary layer provides efficient long-range propagation conditions for LFN (Waxler et al., 2006, 2008). Conversely, during the daytime conditions the formation of such waveguides typically do not exist, and sound refracts upward, away from the source. The anisotropic propagation patterns follow from the direction dependence of the effective sound speed.

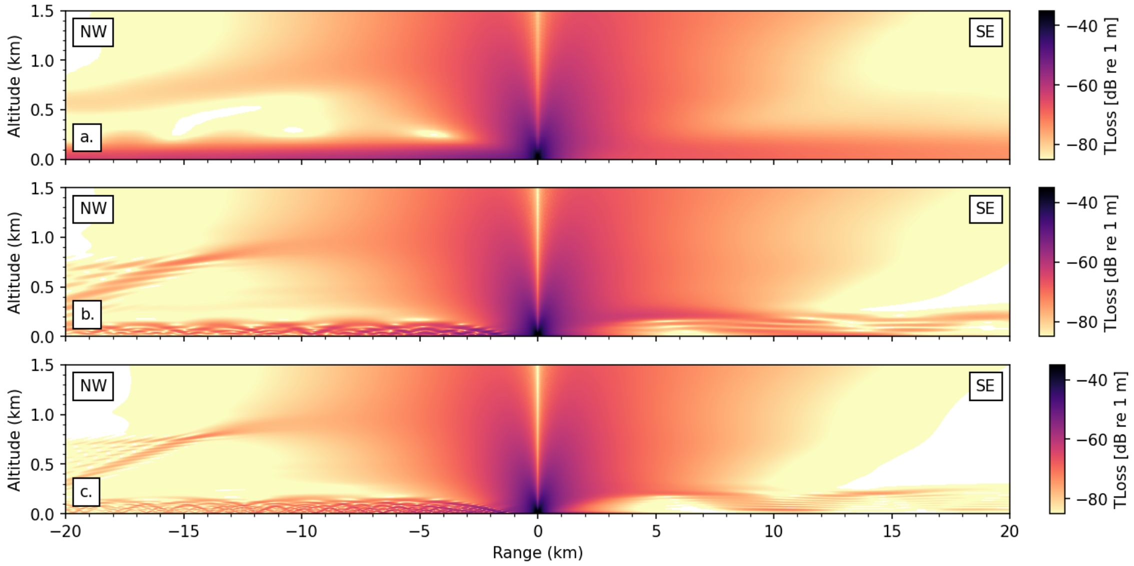


Figure 12 Simulations using a full-wave propagation model (e.g., Waxler & Assink, 2019) *at (a) 5 Hz, (b) 50 Hz, and (c) 100 Hz based on the atmospheric profiles show in Figure 9. The simulations show an anisotropic propagation pattern due to the influence of the winds. Propagation towards the NW is more efficient because of the prevailing wind from the SE. The temperature inversion near the ground plays a role as well, and patterns vary strongly with frequency.*

Besides its influences on refraction and scattering, the atmosphere also plays a role in the absorption of sound. The absorption coefficient is proportional to the frequency of sound squared (Figure 9), so high frequencies tend to attenuate faster (Sutherland & Bass, 2004). In the lower atmosphere, losses are predominantly caused by vibrational relaxation for which acoustic energy is transferred to the vibrational modes of the air molecules (N_2, O_2, N, O, CO_2, O_3, and H_2O). Since the air becomes drier with increasing altitude, the attenuative effects of humidity (e.g., in the case of mist) are strongest in the lower troposphere.

Engineering models have been designed for the mapping of environmental noise (also with frequencies beyond the LFN range), such as the Harmonoise model (Salomons et al., 2011). Such models assume sound speed profiles with a linear dependence with altitude. Comparisons between the Harmonoise model and reference solutions, which have been carried out for various case studies up to distances of several hundred meters, show that such models can be valuable.

It is important to point out that atmospheric propagation can be considered to be a linear process (Pierce, 2019). An important implication is that no higher or lower frequencies can be generated along the propagation path. It is, however, possible that the distribution of the spectrum shifts to lower frequencies along the propagation path since higher frequencies attenuate more quickly. Indeed, the received frequency (f) spectrum $R(f)$ from a source with spectrum $S(f)$ can be computed in the frequency domain as $R(f) = S(f)T(f)$, where $T(f)$ represents the transfer function that describes the dispersion (including transmission loss) from source to receiver.

2.4.2 Measurement in a turbulent atmosphere

The LFN wavefield is complex and consists of transient signals that are embedded in a background of incoherent and coherent acoustic noise, such as depicted in Figure 3. The incoherent signals are non-acoustic signals that occur due to processes in the atmosphere, such as incoming radiation and the presence of wind near the acoustic sensor. Both processes can generate pressure fluctuations that can mask acoustic signals of interest, in particular at infrasonic frequencies (Figure 3). To obtain accurate acoustic measurements, it is therefore typically needed to apply wind screens to reduce the effect of wind noise. The wind screens scale with the frequency of interest, as the characteristics of the wind noise are frequency dependent.

The following components of wind noise have been classified (Raspet et al., 2019):

- Intrinsic turbulent pressure due to convection in the lower atmosphere. This subcategory can be subdivided in:
    a. Turbulence-shear interactions: this category is dominant at low-frequencies and near the ground where wind shear is largest.
    b. Turbulence-turbulence interactions: dominant at higher frequencies and typically masked by turbulence-shear interactions.
- Stagnation pressure: the influence of wind on the sensor makes that the pressure signal of interest (static pressure) is perturbed by wind.

The pressure spectrum of turbulence has been described statistically to decay with a slope of $f^{-5/3}$. This implies that the effect of wind noise increases towards lower frequencies (Raspet et al., 2019). At infrasonic frequencies, wind noise typically masks the background acoustic noise when turbulent processes in the lower atmosphere prevail, typically during daytime. Regarding stagnation pressure, it follows from analysis of Bernoulli's equation that a wind of 1 m/s corresponds to a pressure perturbation of 1 Pa. Typical acoustic signals of interest have amplitudes that are one to two orders of magnitude lower. The effects of stagnation pressure can be reduced by placing microphones in sheltered places, for example near the ground since the wind speed tends to increase logarithmically with altitude.

The atmospheric boundary layer, or the lower 1.5 to 2 kilometers of the atmosphere, has a special role in both the propagation and perception of sound (Figure 13). As discussed in Section 2.4.1, sound can propagate efficiently under certain meteorological conditions, such as temperature inversions and low-level wind jets.

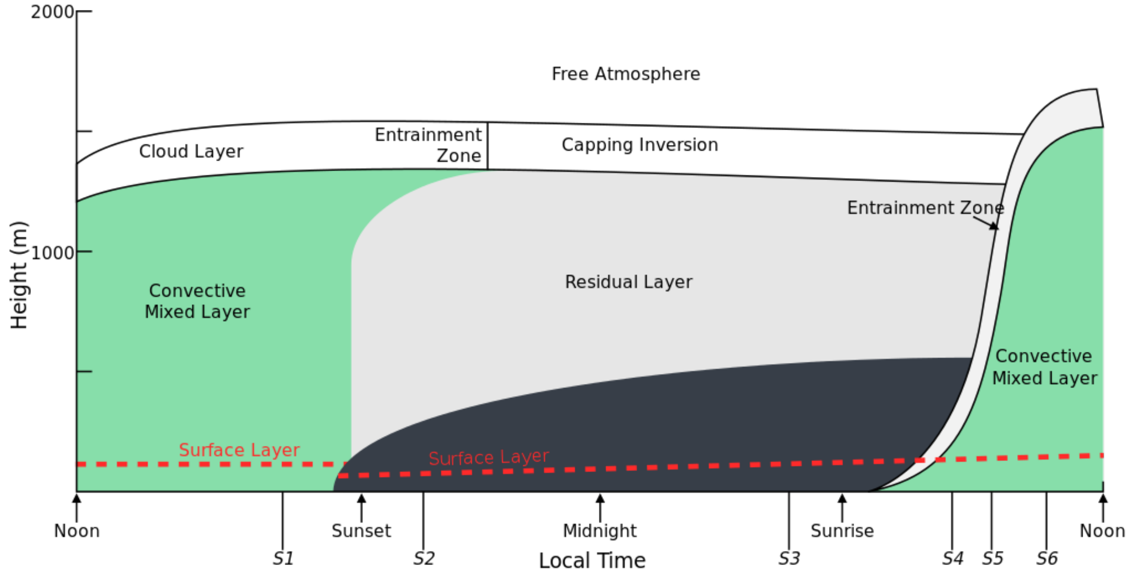


Figure 13 Transition between a convective boundary layer during the day to a stable boundary layer at night. Figure adapted from (Stull, 1988)*. License: Creative Commons Attribution-Share Alike 3.0*

During the day, the boundary layer is well mixed by convection. In the afternoon, under the influence of the warming of the Earth's surface, thermal plumes occur that rise and fall in the boundary layer and thus cause thermal turbulence. The turbulent mixing doesn't saturate until afternoon. Mechanical turbulence is generated due to the increased wind shear near the ground surface and the friction due to the interaction the ground surface. Above the boundary layer is the 'free' atmosphere, where the wind is in geostrophic balance, i.e., in balance with the air pressure gradient and the Coriolis force (Stull, 1988).

After sunset, the boundary layer becomes stable due to a decrease in incoming radiation under clear skies. Stable conditions inhibit vertical and horizontal mixing near the ground and consequently, favor the development of a surface temperature inversion. Temperature inversions form rapidly around sunset and dissipates equally rapidly around sunrise. As a result, the wind at the earth's surface also decreases in strength. As a result, the former mixing layer is uncoupled from the surface. This has several implications for LFN:

1. The temperature inversion corresponds to an adiabatic sound speed inversion, which provide efficient long-range propagation conditions (e.g., Waxler et al., 2008). This is further discussed in Section 2.4.1.
2. During stable conditions, the mechanical and thermal turbulence is suppressed, which reduces the scattering of the sound.
3. Finally, the turbulence suppression also ensures low wind noise levels, thereby lowering the detection threshold.

Under cloud cover the atmosphere is approximately neutral and temperature inversions are (less) pronounced. In practice, this means that the propagation is completely controlled by winds throughout the atmospheric boundary layer.

2.4.3 Effect of the ground surface and the subsurface

The ground surface has several effects on the LFN field that include (1) reflection, (2) attenuation, (3) scattering and (4) conversion to seismic energy.

The ground surface constitutes a boundary for acoustic propagation models (Salomons, 2001) and is typically modeled as a porous medium or half space. Mathematically, such boundary conditions are represented by a complex impedance. For many natural ground types, frequency-dependent impedance models have been derived (Waxler et al., 2006). Impedance values are typically higher at lower frequencies and for harder ground types and vice versa. Harder surfaces are reflective, softer bottoms more compliant and absorptive to sound. The interaction with the subsurface is not yet well understood at very low frequencies for which impedance models are not well characterized. Studies (Assink et al., 2018; Shahar Shani-Kadmiel et al., 2018) have shown that the seismic and acoustic wavefields readily couple at low acoustic frequencies. Modeling studies using coupled seismoacoustic models (Averbuch et al., 2020) suggest that sources in softer bottoms couple better to the atmosphere. Scattering of LFN is also possible through the presence of barriers on the ground surface, such as concrete buildings, or the presence of topography (Emmanuelli et al., 2021). Scattering effects increase as the size of the scatterer approximates the wavelength of the sound.

The subsurface itself plays a further role in the propagation of vibrations. There are several mechanisms that simultaneously affect the elastic motion in unconsolidated bottoms typical of the Netherlands (van Ginkel et al., 2019):

1. Due to soft sediments with low shear wave velocities at shallow depths, ground motion is amplified as seismic waves propagate upward
2. Soft sediments also lead to enhanced attenuation of the seismic wavefield, in particular at higher frequencies
3. Resonances occur due to reverberations in a shallow soft layer and a harder layer at depth.

An integrated shear wave model has been formulated for the Groningen area, up to a depth of 1 km. The uppermost 50 meters is derived from seismic cone penetration tests (Kruiver et al., 2017). Van Ginkel et al., 2020 show that the Horizontal vs. Vertical Spectral Ratio (HVSR) from the ambient seismic field can be used to estimate to first order wave amplification. In the Netherlands, amplification factors may peak in the 1-4 Hz range, which corresponds to resonance frequencies of Dutch houses (Crowley et al., 2019). At higher frequencies resonance effects are reduced due to seismic wave attenuation.

While it is likely that for LFN from airborne sources the airborne path is dominant, it is also important to consider the geological site effects as well as resonances in the building itself, certainly for subsurface sources such as induced earthquakes. Airborne LFN can cause vibration of windows and walls which can be measured. Both vibrational and sound measurements inside and outside the dwelling are recommended to be able to quantify the source levels and the effects of the building.

2.5 Transfer functions of dwellings

It is common practice to assess the impact of LFN on humans indoors, whereas LFN is usually measured outdoors. To be able to translate the LFN wavefield measured outdoors to the indoor situation, we need to rely on transfer functions. Low-frequency sound insulation of façades of buildings is usually expressed as the level difference between the incident outdoor level and the level inside the room. At low frequencies, the sound field normally varies substantially with the position within the room. This is due to standing waves causing a pattern of nodes (where the amplitude is minimum) and antinodes (where the amplitude is maximum). When measuring the low-frequency sound insulation of façades, spatial variance of the sound field should be acknowledged.

For evaluation of LFN complaints, sound insulation is usually based on the positions where the room occupants perceive the noise as being loudest. This results in presumably the highest indoor sound level and thus lowest insulation value. Often, the complainants are unable to determine the location of these 'hot spots'. In that case positions are picked that are usually occupied by the complainants. A worst-case approach is to measure in the corners of the room (3D measurements), ensuring levels near the highest in the room.

The international standard ISO 16283-3:2016 provides a widely used method for measuring the airborne sound insulation of façades of buildings and building elements. The quantities are to be measured using one-third octave band filters with the center frequencies spanning from 100 Hz to 3.15 kHz. The method does aim at the average sound level in the room instead of the maximum. If additional information in the low-frequency range is required, the method provides in a special procedure for the 50, 63 and 80 Hz center frequencies. The large spatial variance of LFN is accounted for by additional measurements in the corners of the room, where the amplitudes of the noise are near highest. The corner measurements are necessary to improve repeatability and reproducibility of the method. At the same time, corner measurements ensure that the sound level is more in line with the maximum sound level in the room. The low-frequency procedure is restricted to rooms smaller than 25 m^3 and is yet rarely included in standard studies.

A Danish survey gives an overview of two measurements campaigns of low-frequency sound insulation of dwellings (Hoffmeyer & Jakobsen, 2010). Several indoor microphone positions were used, allowing to obtain the average sound level in the room as well as the near to maximum sound level. The data was also compared to literature, including data from The Netherlands (Vercammen, 1992). The Danish researchers found good agreement between the Danish and Dutch measurements, after correction for the microphone placement. The Danish data was treated statistically and the level difference that is expected to be exceeded by 80-90% of the typical Danish dwellings was compiled. This data is widely used as a reference, including assessment of LFN from wind turbines (Table 2).

f [Hz]	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
ΔL_σ [dB]	2.4	1.2	3.2	2.1	3.6	4.6	6.7	7.6	10.3	14.2	17.5	18.4	17.5	18.6	22.4

Table 2 Level difference in dB expected to be exceeded in 80-90% of typical Danish dwellings.

The results of the survey have been debated by Møller and Pedersen (Møller et al., 2011). These researchers claim that the measured indoor measurements that were used to calculate the 80-90% exceedance level do not agree with the positions where the noise levels are loudest but are more likely to correspond to average levels. Therefore, Møller and Pedersen claim that the data cannot be used to estimate indoor sound levels relevant for assessments at low frequencies.

A development in building construction is the application of lightweight building structures. Because the insulation of facades at low frequencies strongly depends on mass, insulation values may decrease and thus an increase in nuisance due to low-frequency noise. Innovative solutions in the construction of facades should counteract this problem (Norén-Cosgriff et al., 2016).

A potential complication problem in assessing LFN indoors is the occurrence of binaural effects. Standing waves in a room will result in small pressure differences on both ears of the room occupant. These pressure differences can possibly enhance annoyance. Binaural effects are not considered when determining the façade insulation according to the above-mentioned monaural methods. Binaural effects on human beings are currently subject of study.

3 Sources of LFN

3.1 Introduction

In this chapter we focus on the sources relevant for the generation of LFN in the mining industry. As in the rest of this study, mining activities refer to production, transportation and storage of gas, as well as activities related to the production of geothermal energy and salt. The objective of this chapter is to create an understanding of generation processes of LFN from mining activities. The selection of considered sources is based on the Request for Proposal of the client and on the relevance according to experts interviewed. The noise generation mechanisms of these sources is explained both in general and for LFN specific.

3.1.1 Relevance

The sources as described are not equally important for the generation of LFN. It shall be recognized however, that the generation process itself is only a single link in the complex chain between source and receiver. LFN problems generally only pop up in a favorable concurrence of circumstances. For example, when the excitation frequency of the source coincides with a resonance frequency in connected piping, the encapsulation of the machinery, the façade of the building, or a standing wave frequency of the room. Such resonances can be important both on the source and on the receiver side. The efficiency of the sound transfer between source and receiver may also vary in time and place, as this is dependent on favorable atmospheric conditions. As a result of these varying environmental circumstances, there is a scatter in the importance of noise sources. Primary sources will not automatically lead to complaints and secondary sources may lead to complaints if the circumstances are favorable.

In the Netherlands, mining facilities are often located in rural areas where background noise levels are low. Therefore, annoyance may arise at very low levels. Although LFN is often experienced as a feeling in the body rather than an audible sound, it has been shown that residents of quiet rural environments are more distressed by sources than residents of urban regions (Hessler, 2005). This points to the relevance of understanding the way in which LFN problems might arise. Furthermore, typical mitigation measures reduce mostly mid- and high frequencies. An example is presented in Figure 14, which presents the attenuation of a noise barrier and a façade. The reduction is significant only at higher frequencies. The same holds for example for regular piping insulation, which only reduces higher frequencies effectively. Piping insulation may even lead to an increase at lower frequencies as a result of an increased diameter and characteristics of the radiation efficiency. As a result of applied mitigation measures, noise emitted from mining facilities and from industrial facilities in general, becomes more low frequent in nature as lower frequency bands of the spectrum start to dominate (Nilson and Berglund, 2006).

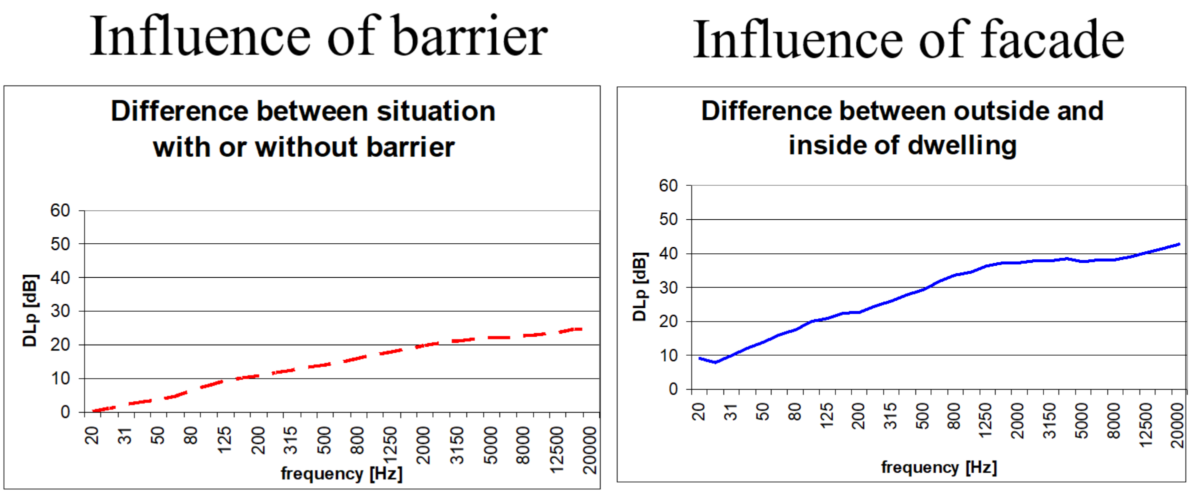


Figure 14 Example of the frequency dependent attenuation of a noise barrier (left) and a facade (right)(De Graaff, 2005)

3.1.2 Generation processes

Many different generation processes of LFN exist. With regard to equipment, LFN may be generated either as a result of mechanical vibrations of machinery parts, or as a result of acoustic pressure pulsations within the system. An overview of possible pulsation sources is provided in Figure 15, including their characteristic frequency range. In the case of pipes, LFN may be generated by flow-related processes such as vortex shredding and turbulence, amongst others. Lastly, when it comes to earthquakes, LFN may result from the conversion of seismic energy into acoustic energy.

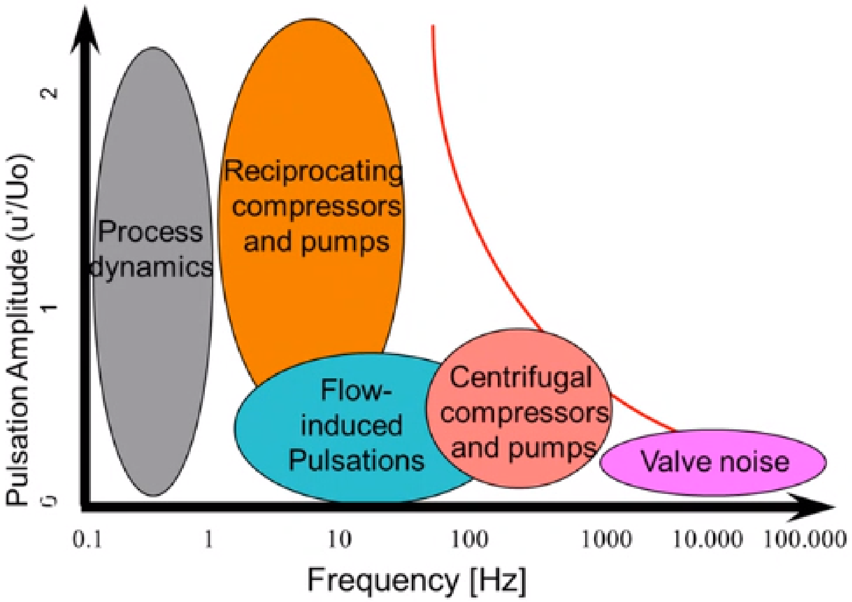


Figure 15 Amplitude-frequency characteristics of various pulsation sources used in the mining industry. Courtesy of TNO.

To understand the generation of noise from rotating machines, it serves to differentiate between several steps in the generation process: 1) which forces arise in the machine, 2) which components are exposed to these forces and what is the transmission path to those components, and 3) how efficient are these different components in radiating vibrations as sound. Here, we will briefly touch on these three topics. Although the input parameters described below are hard to accurately predict, their mutual relation provides insight in the way in which noise levels may be reduced (Granneman, 2017).

1. A common example of forces within a machine are imposed vibrations resulting from force excitation. A changing force F induces vibrations with a specific vibrational speed v_i in the system. The magnitude of v_i depends on the input impedance Z and input force F, both of which are frequency dependent.

2. The transmission of imposed vibrations to other parts of the system can be characterized as the ratio H between induced vibration v_i and vibrational speed v_0 perpendicular to the radiating surface. This ratio H is frequency-dependent and might be used to calculate v_0 if known. H depends on several machine characteristics such as the type of material, which defines the vibrational damping, and mechanical coupling between components which impose additional damping and isolation. Rigid connections such as boulted mounts or welded connections impose little damping; elastic layers and vibration-isolated coupling damp more. The lower the vibrational frequency, the more rigid an elastic material is to that vibration and the less effect it has on the sound reduction.

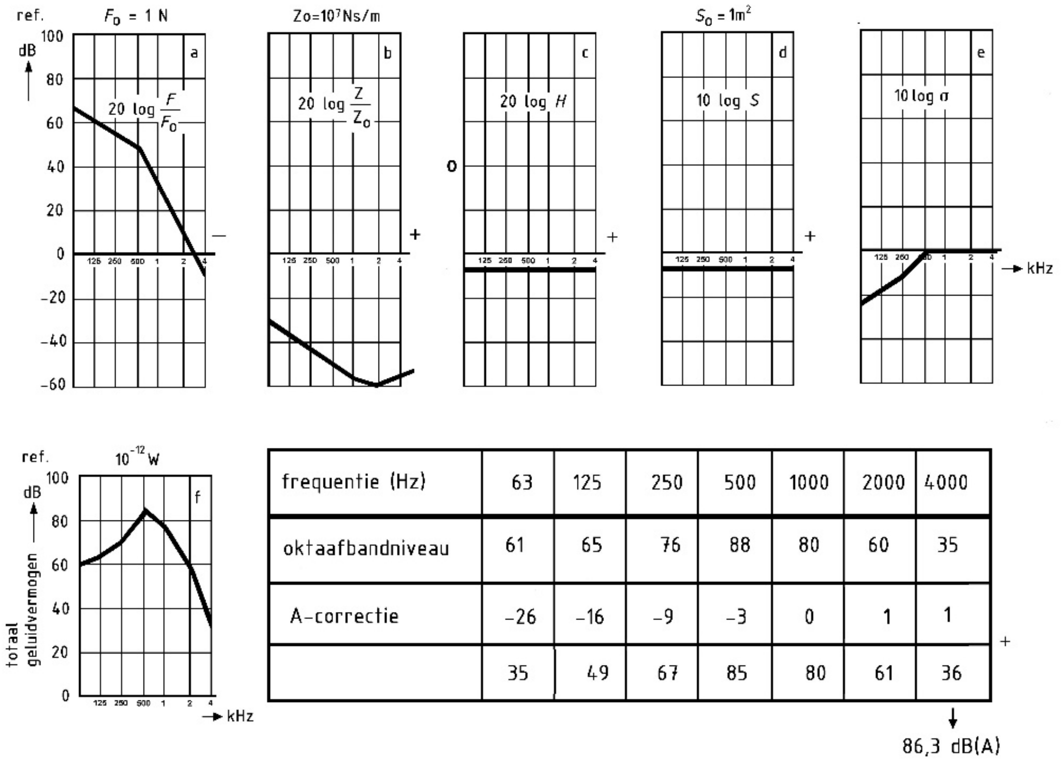
3. The radiation efficiency of a construction is characterized by the frequency-dependent sound radiation factor σ(f). The radiation efficiency is larger for higher frequencies.
If the parameters are known, the frequency dependent sound power level $L_W(f)$ of the radiating object can be calculated as (Granneman, 2017):

$$Lw(f) = 20log\frac{F(f)}{F_0} + 20logH(f) - 20log\frac{Z(f)}{Z_0} + 10log\frac{S}{S_0} + 10log\sigma(f)$$

with
$W_0 = 10^{-12}$ W
$F_0 = 1$ N
$Z_0 = 2 \cdot 10^7$ Ns/m
$S_0 = 1$ m^2

From the equation it follows that noise levels can be limited by reducing the impulse force, transmission, size of radiating parts or sound radiation efficiency, or by increasing the input impedance.

In Figure 16, an example is provided of the A-weighted sound power level resulting from a frequency-dependent impulse force F. In this example, although F is mostly low frequent in nature, the resulting sound power level has a peak around 500 Hz. This is explained by the frequency-dependence of the impedance Z and the radiation efficiency σ, on the one hand, and the A-weighting on the other.



frequentie (Hz)	63	125	250	500	1000	2000	4000
oktaafbandniveau	61	65	76	88	80	60	35
A-correctie	-26	-16	-9	-3	0	1	1
	35	49	67	85	80	61	36

86,3 dB(A)

Figure 16 Example of the produced sound power level from a frequency-dependent impulse force. From (Granneman, 2017).

The example in Figure 16 is simplified for a general understanding of the principal and given for an averaged effect in (broad) octave bands. In many practical circumstances however LFN only shows up in in narrow frequency bands, e.g. when the blade passing frequency of a gas turbine coincides with a resonance frequency of the stack, or when the frequency of vortex shedding in a pipe coincides with a quarter wave length resonance in a side branch. The radiation efficiency of plate like structures is in generally very low at low frequencies, but the radiation efficiency of a pipe breathing mode can be quite high. This means that the radiation efficiency of sources may vary significantly over a small frequency range. A small shift in the operating speed of rotating equipment may have huge effects on the LFN radiated.

3.1.3 Mining industry

In the Netherlands, mining activities are related largely to the extraction, processing, transportation, and storage of natural gas. To a lesser extent, mining activities are related to the extraction of salt and increasingly facilities for geothermal heating. In the following paragraphs, a short description of mining activities is provided, including the type of equipment used.

__Gas production__

Gas is extracted from the reservoir and redirected to a gas treatment plant through a piping system. Extraction of gas takes place both onshore and offshore. Gas gathering compression might be needed to raise gas from the wellhead pressure to 70-100 bar for transportation to a gas processing plant (DHV B.V., 2008).

Extracted gas is ‘wet’ when operated on with evaporated liquids such as condensates (natural gas liquids) or water (B. White et al., 2018). It is a mixture of pure natural gas, water and condensate. In the treatment facility impurities are removed and treated. Pumps are used for auxiliary chemicals such as methanol, glycol, and a corrosion inhibitor. Regeneration furnaces regenerate the silica filters, or the glycol used in the process.

Gas storage

In the Netherlands, underground gas storage (UGS) facilities are created in depleted gas reservoirs. The gas is contained in a porous sandstone layer - the reservoir. Gas storage is carried out to handle seasonal changes in demand.

Extraction from the gas storage is similar to the process of gas extraction. Because gas temperatures rise when pressurized, cooling is applied (B. White et al., 2018). Because injection requires higher pressures than withdrawal, injection compressor stations are often more costly and have more power than facilities for extractions. Because equipment has to adapt to a wide range of operating conditions, reciprocating compressors may be used for these types of facilities, although in the Netherlands, centrifugal compressors are mostly used. Because of the large variety in storage conditions, often operation is carried out using multi-stage compression (B. White et al., 2018). Variable frequencies might be used.

Apart from natural gas injection compressors, pumps are deployed for injection of methanol, corrosion-inhibitor and production water.

Gas transportation

Gas is transported through a piping network, which in the Netherlands is administered by Gasunie. Two separate piping networks exist, one for low calorific and one for high calorific gas.

Along the pipe, there will be pressure losses correlated with the flow velocity and length of the pipe (B. White et al., 2018). Therefore, compressor stations are used to boost the pressure to maintain a rough 55-65 bar along the piping in the case of the Netherlands. In the Netherlands, there is a compressor station roughly every 80 km. Compressor stations are in use mostly during peak demand in cold winter days. In the Netherlands, both electrically and gas turbine-driven centrifugal compressors are used for this purpose, both of which are placed indoors.

Apart from compressor stations, there are blending stations, Metering & Regulation (M&R) stations that reduce high-pressure (55-65) to medium pressure (40 bar), and gas receiving stations where gas is further depressurized to about 8 bar.

Extraction of salt

The process of extracting salt consists of pressurized water being pumped into the salt containing caverns. In the Netherlands, salt caverns are located at depths between 100 and

5000 meters. The salt is dissolved by the high pressured water and the resulting brine is pushed up. At the surface, the brine is captured in atmospheric storage tanks. High pressure reciprocating pumps are typically used for the purpose of delivering the necessary pressure. In between the cavern and the tanks, there are high- and low-pressure pipelines and chokes. Salt can be extracted from the brine by means of evaporation using boilers.

Geothermal heat

Geothermal energy is extracted from water located at depths of 2 to 3 km underground. The geothermal facility consists of two wells: one for the extraction of water by means of an electrical submersible pump inside the well, and the other for injection. For injection, around 60 bar pressure is needed for which multistage centrifugal pumps are used. These are electrically driven. In addition, smaller pumps are used to realize pressure in the facility, typically less than 16 bar. The injection pumps are most relevant as a possible source of LFN.

3.1.4 Scope

In this study, the following possible sources of LFN are considered in more detail: rotating equipment (compressors, pumps, gas turbines, fans), furnaces, flow of liquids and gas through pipes, and man-induced earthquakes. Other sources of LFN exist but are out of the scope of this study. The selection of considered sources is based on the Request for Proposal and on the relevance according to experts interviewed. In Table 3 a list of possible sources of LFN is provided, ranging beyond the sources considered in this document.

In this study, we focus on the permanent operating conditions of mining facilities; we do not consider the construction phase.

Table 3 Possible sources of LFN

Type of equipment	Relevance for LFN
Compressors	Possible source of LFN. Fundamental frequencies are related to the rotational speed and the number of blades / vanes / lobes / pistons. For reciprocating compressors, the fundamental frequency and first harmonics are in the low frequency range. For centrifugal compressors they are not, however LFN may be emitted in some occasions, for example at frequencies corresponding to the rotational speed as a result of imbalance, misalignment or unequal blade distribution.
Pumps	Possible source of LFN. Generation of LFN similar to compressors. Fundamental frequencies are related to the rotational speed and the number of blades / vanes / pistons. For reciprocating pumps, the fundamental frequency and first harmonics are in the low frequency range. For centrifugal pumps they are not, however LFN may be emitted in some occasions, for example at frequencies corresponding to the rotational speed as a result of imbalance, misalignment or unequal blade distribution.
Gas turbines	Used in some facilities as compressor drivers. Possible source of

	LFN, in particular from the exhaust. Unlike pumps and compressors, gas turbines do not transmit most of its vibrational or acoustic energy to connected parts such as the piping system, but emit LFN directly from the exhaust.
Pipe system	Possible source of LFN. Radiation of vibrations and acoustic pressure waves generated elsewhere. LFN from flow of gas or liquid in pipe, especially due to vortex shedding.
Furnaces and boilers	LFN predominantly radiated by the fan stack. Very high LFN levels are emitted when thermoacoustic vibrations occur.
Motors (electric, combustion)	Possible source of LFN.
Coolers	Possible source of fan-related LFN. Principle similar to centrifugal compressors. Fundamental frequencies are related to the rotational speed and the number of blades. If the rotational speed is low enough, this can be a source of LFN.
Transformers	Possible source of LFN at the fundamental frequency of 50 Hz and harmonics.
RC filters (capacitors and coils)	Possible source of LFN.
Flaring and blowdown systems	Possible source of LFN. Temporary events.
Valves (choke / safety HIPPS / anti-surge)	Possible source of LFN.
Screw conveyer	Has been known to produce LFN when obstructed.
Process dynamics	Possible source of LFN.
Diesel engine vehicles on site	Possible source of LFN.

3.2 Rotating equipment

3.2.1 Generation processes

Several aspects related to the radiation of noise generated by rotating equipment are discussed in this section.

Fundamental frequency and higher harmonics

The mechanical behavior of rotating equipment inherently causes vibrations and pulsations. These lead to emission of noise at a series of frequencies related to the rotational speed and the number of events per rotation. The fundamental frequency of the spectrum depends on the rotational speed times the amount of events per rotation, such as number of gear teeth, fan blades, pistons etc.

$$f_0 = \frac{1}{T} = \frac{n}{60} * z$$

with
f_0 = fundamental frequency (Hz)
T = time period between events (s)
n = rotational speed (rpm)
z = number of events per rotation (-)

Every event leads to an impulse like force and consequently to an impulse like vibration and noise radiation event. As the events repeat every rotation, this leads to a regular series of impulses or a pulse train.

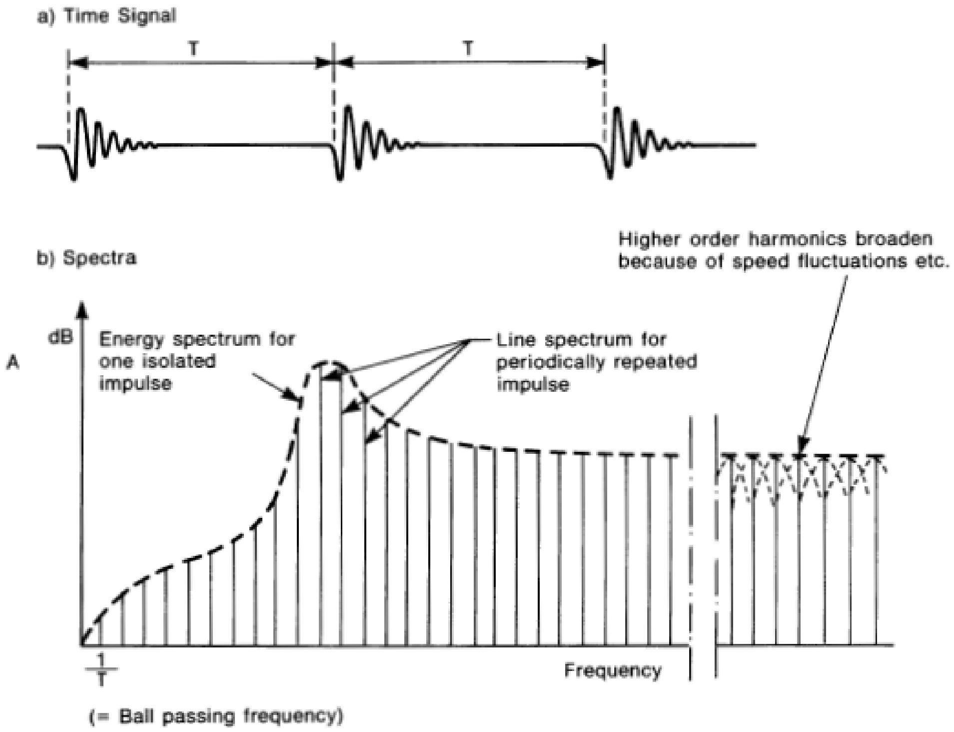


Figure 17 Frequency content of a time signal consisting of a pulse train with period T in between pulses.

The principal relation between pulse characteristics in the time domain and the spectral content in the frequency domain, is represented in Figure 17, depicting the time and frequency characteristics of a pulse train. In the time domain, the vibrations caused by passing fan blades or oscillating pistons are recurrent pulses with a period T in between related to the periodic impulse-like signal. In the frequency domain, this time signal results in a frequency spectrum with a fundamental frequency f_0 corresponding to the repetition period T. As excitation forces are not purely sinusoidal, higher harmonics at 2x f_0, 3x f_0, 4x f_0 etc. are typically present in the frequency spectrum. The more abrupt and steep the pulse shape is in the time domain, the more higher harmonics are available in the frequency domain. The envelop of the resulting line spectrum corresponds to the energy spectrum of one isolated impulse and the dominant frequency range depends on the shape of the pulse (De Graaff, 2021).

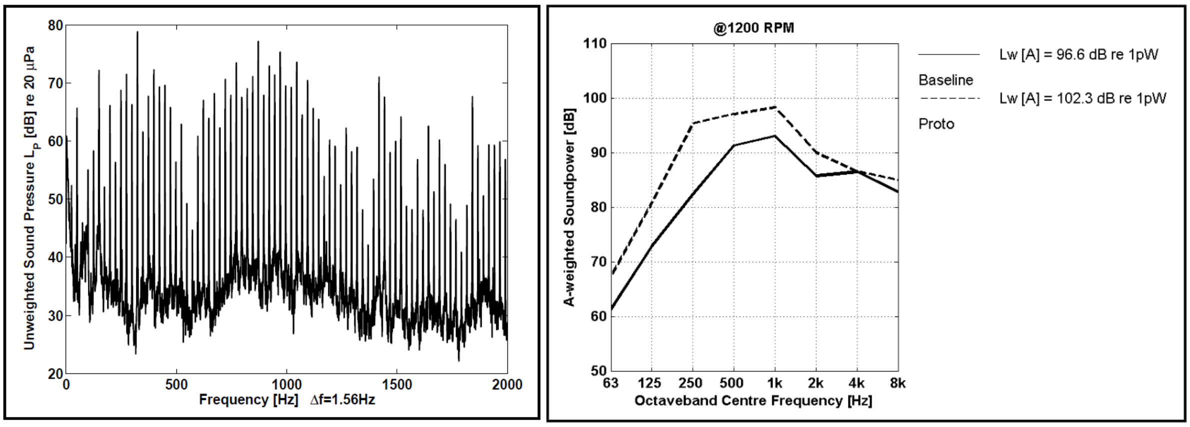


Figure 18 Sound measurements on a reciprocating compressor. From (Roozen et al., 2009). *Left: linear-weighted narrow band analysis, Right: A-weighted octave band analysis*

A typical frequency spectrum of a small reciprocating compressor is shown in Figure 18 (Roozen et al., 2009). This figure gives two different analyses of the same machine. The left is a linear-weighted FFT narrow band spectrum. The right is an A-weighted octave band analysis. The narrow band analysis shows the fundamental frequency of 20 Hz corresponding to 1200 rpm, and some hundred higher harmonics (40, 60, 80 Hz etc.). The subjective appreciation of the human ear and brain recognize this pattern of a fundamental frequency with higher harmonics as a low frequency 20 Hz base tone with some higher frequency tone coloring. Just as in Figure 17, some of the higher harmonics actually radiate 10 or 20 dB more efficiently than the fundamental frequency of 20 Hz. This indeed leads to a high frequency coloring, but also adds to the subjective appraisal of the low fundamental frequency. In fact, the human brain may reconstruct the fundamental frequency from the higher harmonics, even if the fundamental frequency itself is not available in the spectrum. This effect of “missing fundamental” or “Tartini tones” is elaborated in Section 4.4.

The FFT narrow band analysis is a suitable tool for the engineer to recognize this pattern and the fundamental frequency. Various other tools, such as order analysis or Cepstrum analysis are available to analyze the periodicity of the signals. The A-weighted octave band analysis on the right gives a different interpretation of the same time signal and highlights the traditional peak in the sound energy spectrum around 1000 Hz. This may lead reduction measures to focus to the 1 kHz region, as the main part of the acoustic energy is bundled there. The octave band analysis however neglects the LFN issues related to the fundamental frequency of 20 Hz. In many cases octave band analysis may therefore not be very suitable the handle LFN issues.

LFN related directly or indirectly to rotating equipment is therefore mostly tonal (Van Lier et al., 2006) even if the octave band spectrum would not suggest this. Tonal noise is assumed to be more annoying and therefore assessed more strictly by law in many European countries (Peeters & Nusselder, 2019). More information on health effects and noise legislation can be found in chapter 4.

Radiation via Pipe systems and Structural steelwork

In many cases, the most relevant contribution of the radiate noise does not come from compressors and pumps themselves, but from the connected pipe system. In several cases noise radiated from the pipe system led to relevant noise levels at mining facilities (Baars, 2007; Van Lier et al., 2006). Energy may be transmitted either by mechanical vibrations or by acoustic pulsations. The radiation of LFN from pipes is discussed in chapter 3.3. Because the pipe system can play an important role in the radiation of LFN generated by the equipment, noise reducing measures should be primarily aimed at reducing levels directly at the source: the machine. That way, both noise from the source and from the pipes is addressed simultaneously.

Apart from the pipe system, other parts in the facility may be excited by mechanical vibrations or acoustic pulsations from the equipment, such as the machinery foundation, enclosure walls, accessory machinery or supporting steel structures. Regarding structural steelwork, a large part of radiated noise results from vibrations transmitted from the piping to the steel frame via the pipe supports (Baars, 2007)

The acoustic radiation efficiency determines whether vibrational energy is converted efficiently into sound. The radiation efficiency depends both on characteristics of the vibration – strength, frequency, waveform – and characteristics of the radiating component – in particular the surface area, the geometry and mechanical characteristics. In the case of a steel frame, most important are the vibrational frequency and the circumference of the beam. Thin pipes and steel profiles radiate at higher frequencies, whereas larger parts may radiate both at higher and at lower frequencies. The strongest levels are to be expected when peaks in the excitation spectrum correspond to the vibrational resonance modes of the frame. Broadband excitation may lead to resonances as well, although less strong vibrations and noise can be expected (Baars, 2007).

To prevent vibrations and noise from structural steelwork, apart from measures at the source, care should be taken to use vibration-isolated pipe supports and prevention of mechanical connections between the steel frame and equipment. Furthermore, coincidence of excitation and resonance frequencies can be prevented or taken away by adding additional mass, stiffening or damping to the system (Baars, 2007). As steel structures in facilities are often large, interference between the sound field of different radiating steel profiles and pipes may lead to complex sound fields (Baars & Nieuwenhuizen, 2004).

In facilities where rotational speeds of compressors are variable, different resonance frequencies within the structure of the facility might be excited, meaning that different parts of the facility might radiate sound at different operating conditions (Baars & Nieuwenhuizen, 2004). This can be a complicating factor when trying to identify and solve noise-related issues.

Operating conditions and design choices

Emission of LFN by rotating equipment is related directly to the operating conditions of the machine. The frequency content of the noise signal is related to the rpm of the machine and the number of pulsations per revolution. The spectrum also depends on design choices, for example: the shape and amplitude of pulsations resulting from reciprocating machinery depend on geometrical characteristics and on system parameters such as the crank / rod ratio, the piston volume and valve settings, amongst others (Van Lier et al., 2006). As a change in the frequency content of the spectrum may have a great impact on the transmission and possible amplification of vibrations to other radiating parts, operating conditions and design choices are crucial when it comes to both preventing and mitigating emission of LFN. In addition, low frequency sound pressure amplitudes may increase with load such as is typical in the case of gas turbines (Hessler, 2005; Kudernatsch, 2000).

The relevance of operating conditions is illustrated in the following example of a reciprocating compressor (Figure 19). Here, the pulse shape is given for two operating conditions: one with reverse flow capacity control installed, resulting in a steeper pulse shape (blue), and two the traditional valve-lifting capacity control (red). The corresponding A-weighted frequency spectra are shown in the right-hand side of the figure. The steep gradient of reverse flow leads to more energy in the higher frequencies. This is problematic from the point of view of noise legislation as the overall noise level in dB(A) is higher. However, noise levels in the 16 Hz frequency band are significantly lower for reverse flow. Whereas traditional valve-lifting is preferred from the point of view of complying with noise limits, when it comes to LFN, this method is worse. In particular if acoustic or vibrational modes in the system correspond to the 16 Hz frequency band.

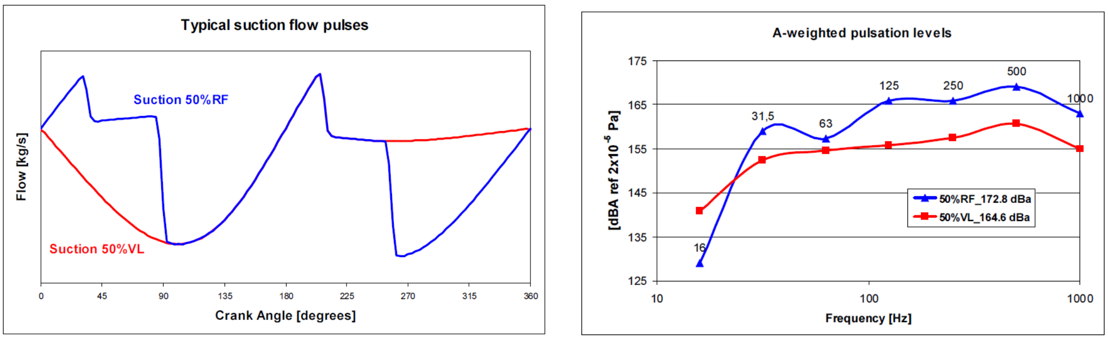


Figure 19 Flow pulses (left) and A-weighted pulse frequency characteristics (right) of a reciprocating compressor with reverse capacity control (blue) or valve-lifting capacity control (red). From (Van Lier et al., 2006)*.*

Foundation

The foundation system is one key to the reliability and noise emission of rotating machinery. A correct alignment is crucial, and the foundation must withstand enough unbalanced forces, and thus must have enough stiffness and mass. A fabricated skid can be used, utilized on a block mounted on concrete, as is typical for large machinery used in UGS sites in the Netherlands (Baars & Nieuwenhuizen, 2004). Vibrational damping is not generally applied, as it results in vibrations and mechanical problems in the machinery. Foundation stiffness may have an impact on the rotor dynamics of the machinery if limited compared to the stiffness of the bearings (Wilkes et al., 2018). The foundation of large rotating equipment is typically dilated from the building foundation to prevent coupling to the building structure.

Standards with regards to support structures and alignment provisions are provided through API 617 and 686 (Wilkes et al., 2018).

3.2.2 Prediction of LFN from rotating equipment

Both with regards to noise emitted directly from the equipment casing, as with regards to noise being emitted elsewhere, information regarding noise emission is relatively scarce (Van Lier et al., 2006). And because the sound power emitted by equipment plus components in a specific facility depends greatly on all the above topics described – transmission path, radiation efficiency, but also: foundation, operating conditions – it is hardly possible to indicate specific noise levels or frequency spectrums that typically hold for any equipment type. In this chapter, we will therefore indicate the relevance of installations for the emission of LFN, but do not provide noise levels or frequency contents that are to be expected.

For specific equipment types, guidelines exist that can be used to forecast noise emissions. For example, the German guideline VDI-3743 applies to centrifugal pumps. These guidelines are not specifically aimed at low frequency noise but do contain information about the lowest frequency bands. In addition, the guidelines also provide instructions for noise reducing measures.

The finite element method (FEM) and boundary element method (BEM) are a low-frequency numerical method which can be used to predict vibrations and noise radiation due to structural dynamics of the housing of equipment and connected steel structures. In special cases FEM is used by suppliers of large equipment and consultants. Through this analysis technique the main resonance frequencies in the system can be identified, and the effect of stiffening and other measures can be investigated (Baars & Nieuwenhuizen, 2004).

In recent years analysis making use of computational fluid dynamics (CFD) has gained great advancements. CFD can for instance be used to analyze the flow behavior in centrifugal pumps.

Specific prediction tools have been developed over the years. The TNO PULSIM software is used to predict pulsations in the system. Part of the PULSIM software is the Noise Engineering Tool, developed to predict noise levels from fluid machinery and connected pipes, which uses the output of the PULSIM software to calculate noise levels in the environment (Van Lier et al., 2006). In addition, vibrations and pulsations of equipment can be predicted and evaluated against the different API standards. Studies related to pulsation and mechanical response are common practice for large reciprocating pumps and compressors. In the case of turbomachinery, these types of studies may be performed to investigate compressor surge and flow induced pulsations (Van Lier et al., 2006). However, most of these studies are performed with the aim of preventing damage or failure and emission of noise is generally not considered.

3.2.3 Compressors

3.2.3.1 Types of compressors

Compressors are devices that increase the pressure of a gas by adding work. In the mining industry, compressors facilitate gas extraction and injection from wells and pipelines in upstream, midstream and downstream facilities. Compressors operate either dynamically or by positive displacement. Dynamic compressors continuously increase the momentum of the gas, whereas positive displacement compressors increase the gas pressure in a discrete manner, working on distinct portions of the fluid at a time. The appropriateness of a compressor type depends on process requirements and is a function of the required flow rate and pressure ratio (Hoopes et al., 2018). Reciprocating and rotary screw compressors operate by positive displacement and are unique in their capability of covering low-flow applications with high pressure gain. Centrifugal and axial compressors operate dynamically and are typically used for high flow conditions, but limited pressure gain. Multi-stage compressors allow for higher pressure build-ups than single stage compressors.

In general, a compressor consists of the following parts:
- Rotating shaft plus blades / lobes / pistons
- Inlet (suction) and outlet (discharge) pipe
- (interstage) cooling

Compressor drivers include electric motors, natural gas fueled engines and gas turbines. Large reciprocating or screw compressors are typically powered by electric or fuel motors. Centrifugal compressors are powered by electric motors or gas turbines. The availability of electricity or gas to power the machine is of course important for the choice of the driver. Gas turbines can be used if no significant speed variation is needed (Wilkes et al., 2018). Advantages of electromotors are their efficiency, a relatively low noise emission and no local exhaust gas emission. Disadvantages are higher electricity costs (DHV B.V., 2008). In some arrangements, compressors can operate over a range of different speeds. This is possible for example by using electric motors with variable frequency drives (VFDs) or variable speed gearboxes. This way a compressor can be adjusted to different operating conditions. At higher speeds, more head and flow is generated and more power is consumed (Wilkes et al., 2018). Typical rotational speeds of centrifugal compressors are between 3000 and 15000 rpm (50 – 250 Hz). Typical reciprocating compressors speed are between 300 and 600 rpm (5 - 10 Hz).

In the Netherlands, both for injection and compressor station applications, often electrically or turbine-driven centrifugal compressors are deployed.

3.2.3.2 Generation of vibrations and noise

The main generation process of LFN from compressors depends on the compressor type involved. In the case of positive displacement compressors, LFN generation is related mainly to acoustic pressure pulsations in the gas, resulting from the discontinuity of the gas flow. In addition, mechanical vibrations arise as a result of rotating and oscillating masses (Baars, 2007). The fundamental frequency of the noise spectrum corresponds to the rotational speed times the number of pistons. The fundamental frequency and its harmonics characterize the noise spectrum. Because reciprocating units have low rotating speeds and small numbers of pistons, the resulting noise spectrum is low frequent. In the case of dynamic compressors, the blade-passing frequency and harmonics are dominant in the spectrum. As a result of the higher number of blades and higher rotational speeds, noise emission is dominated by the higher frequencies (see Figure 15). However, LFN may be emitted by dynamic compressors in some occasions, for example as a result of imbalance, misalignment or unevenly spaced blades.

In general, the generation processes can be related either to mechanical vibrations in the structure or to acoustic pulsations in the gas. In the continuation of this paragraph, more details are provided on both generation mechanisms.

Acoustic pulsations

Positive displacement compressors inherently cause acoustic pulsations in the gas due to the periodic displacement of the gas and to a lesser extent, pressure equalization processes at the discharge side. The pulsations' main frequency is equal to the compressor speed multiplied by the amount of lobes or pistons (Mueller & Moeser, 2004). Therefore, the frequency spectrum of a reciprocating compressor is dominated by the fundamental rotational frequency and its harmonics. Because of their relatively low operating speed, reciprocating compressors are an important source of LFN. In the case of reciprocating compressors, the shape and amplitude of the pulse depends on compressor geometrical and system parameters such as the ratio crank / rod, the piston volume, the valves settings etcetera. In the case of screw compressors, the pulse shape is determined mainly by the geometrical layout of the lobes and the relation between the internal and external pressure ratio (Van Lier et al., 2006).

For large reciprocating compressors, engineers predict pulsations and specify pulsation dampers and possibly adjustments of pipelines and pipe supports. Smaller reciprocating units are delivered with standard pulsation and/or noise dampers (Baars, 2007). Although pulsations are typically limited by standardized silencer design, relevant vibrational levels may occur if the excitation frequency corresponds to the natural frequencies of piping and vessel geometries and gas properties. These resonances may cause piping and/or vessels to vibrate, and in response acoustic modes associated with silencer vessels, separators and connecting piping may get excited as well. Finite element analysis methods can be performed to predict the modes and shapes. Pulsation amplitudes can be limited through acoustic filter vessels, attenuating most effectively at lower frequencies, passive- or absorptive type vessels, absorptive materials, Helmholtz resonator-type acoustic silencers for higher power screw compressors and orifice plates. Orifice plates are metal plates with single or multiple holes, the latter being deployed typically for frequencies above 100 Hz (Broerman et al., 2018).

In the case of centrifugal compressors, noise emission is typically more high frequency in nature as the blade passing frequency is higher as a result of larger rotational speed and larger number of blades and vanes, as compared to reciprocating units. However, in some cases centrifugal compressors may be prone to the emission of LFN. For example, due to unequal distribution of blades or pressure pulses over the circumference, or by instability phenomena such as rotating stall and surge or near-surge conditions, which may arise at low flow rates. In principle, lower flow rates lead to lower sound emission, but pressure levels increase rapidly at surge conditions. In (Yang et al., 2016), sound pressure levels rose by 17 dB and 28 dB for near-surge and surge conditions, respectively regardless of operating speeds. Under these conditions, strong low frequency peaks appear in the noise spectrum.

To prevent surge, compressors have an anti-surge system consisting of an anti-surge valve in a pipe lateral. When opened, these valves are typically very noisy but not particularly low frequency (Baars, 2007). However, occasionally closed anti-surge laterals may act as quarter-wavelength resonators leading to relevant emission of LFN. This is generally prevented through rules of thumb regarding the positioning of the anti-surge lateral.

Mechanical vibrations

Apart from pulsations in the gas medium, mechanical vibrations may be the source of LFN generation. Important for the generation of such vibrations are the rotor dynamics of the machine. In the case of centrifugal compressors, lateral vibrations may lead to relevant levels of LFN under certain circumstances, as described below. For reciprocating or screw compressors, lateral vibrations are less relevant because of their low operating speed, which is typically below the first critical lateral modes (Broerman et al., 2018). For reciprocating compressors, more relevant is pulsating torque resulting from the moving pistons. Rotor dynamic issues are predicted and prevented by rotor dynamic modeling and analysis in the compressor design stage.

Lateral vibrations generated in centrifugal compressors can be characterized either by forced response, often related to imbalance, or self-excited response. Self-excited response is related to stabilizing or destabilizing forces coming from the bearings, seals and secondary flow passages (Hoopes et al., 2018). A relevant lateral response can be caused by bearing-related issues such as damaged journal bearing surfaces, off-design compressor operation, turbulence in the flow field and mechanical issues such as looseness on the rotor or stator, misalignments, and shaft cracks (Wilkes et al., 2018). Regarding imbalance, forces are usually limited sufficiently by careful alignment of mechanical parts and by correct adjustment of the operating speed. The operating speed should be in between the first and second critical speed, corresponding to first (static) and second (dynamic) imbalance configurations. However, if machinery with a variable frequency is deployed outside of its operating range such that operating speeds approach the first critical speed, strong vibrations may be induced in the low frequency range. The frequency of the imbalance forces corresponds to the rotational speed. API 617 and 684 provide estimation methods and recommendations for imbalance configurations (Wilkes et al., 2018).

In the case of a reciprocating compressor, pulsating torque is imposed with the fundamental frequency and higher harmonics of the compressor speed. A two-throw compressor emits strongly at the second harmonic, a four-throw at the fourth (Hollingsworth et al., 2018). These harmonics lie in the infrasonic and low frequency range.

In addition, torsional vibrations resulting from the rotor dynamics of a compressor could lead to LFN under certain circumstances. Torsional behavior is typically similar for different types of rotating equipment (Broerman et al., 2018). If compressors are driven by a synchronous electric motor or variable frequency drivers (VFD) motor, apart from steady-state events, transient events may occur (Broerman et al., 2018). Various torsional modes may be excited during start-up or short-circuit events due to the significant torques generated, with specifically dramatic effects at the critical speed. (Wilkes et al., 2018). In the design stage, torsional analysis is performed, for example according to the requirements described in API 684.

3.2.4 Pumps

3.2.4.1 Types of pumps

Pumps can be either hydrostatic (positive-displacement such as piston pumps) or hydrodynamic (centrifugal or axial flow). Positive displacement pumps force discrete volumes of fluid from the suction to the discharge pipes. Hydrodynamic pumps increase fluid pressure by imparting a radial velocity via rotation of the impeller blades. As in the case of compressors, most of the sound is radiated from pipelines and pipe supports and other equipment with large surfaces (Baars, 2007). Rotational speeds of centrifugal pumps are around 3000 rpm or 50 Hz. Speeds of reciprocating units are lower, around 500 rpm or 10 Hz.

In the mining industry, high fluid pressures are required. For salt extraction, pressures of around 200 bar may be reached using high pressure reciprocating piston pumps. For geothermal applications, around 60 bar pressure is needed for injection, for which multistage centrifugal pumps are used. These are electrically driven. Pumps are generally set up indoors.

3.2.4.2 Generation of vibrations and noise

As in the case of compressors, noise may be related to acoustic pulsations or to mechanical vibrations of machinery parts.

Acoustic pulsations

Reciprocating pumps induce strong pressure pulsations which are reduced by pulsation damping on both the suction and discharge side. The flow excitations arise as a result of the pistons' movement and the opening and closing of the valves. This leads to a non-constant flow rate. Noise spectra related to these flow excitations are characterized by a strong peak at 2x the rotational speed times the amount of plungers, and another component at 1x the rotational speed times the amount of plungers (Mark A. Corbo, 2005). For example, a triplex pump with a pump speed of 300 rpm would have a strong excitation at 30 Hz (2x) and another peak at 15 Hz (1x). The magnitude of the pulsations increases with pump speed. The magnitude is smaller for larger amounts of plungers in the pump, as the plungers can be phased to smooth the effect.

Dampeners are placed in a standardized manner, mainly for reasons other than noise mitigation: on the suction side, dampeners provide a more constant pressure to the inlet valves, protecting against cavitation; on the discharge side dampeners protect the outlet valves (Tatro, 1986). To limit transfer of pulsations in the suction and discharge pipes, pipes are typically provided with vibration insulated coupling. Pulsation and vibrational analysis and design is described in API 674 and 675.

In the case of centrifugal pumps, generation mechanisms of flow-induced noise include the periodic passing of the impeller blades along the volute, cavitation and turbulence. The wake flow at the impeller outlet is the strongest source (Ismaier & Schlücker, 2009). These pulsations lead to noise spectra with a fundamental frequency at the blade passing frequency, which is not typically in the low frequency range. However, a typical centrifugal noise spectrum also shows a peak at the rotating speed of the shaft, be it less pronounced (Guo et al., 2020; Si et al., 2019). This frequency is typically around 3000 rpm or 50 Hz. This means that, although flow-pulsation noise from centrifugal compressors is not typically low frequent, its low frequency discrete components may excite resonance modes in the connected system of pipes, foundation, and equipment.

Cavitation is the local boiling of the fluid due to low pressure regions in the flow. Noise from cavitation is broadband and dominated by higher frequencies (Guo et al., 2020). Although in itself not a direct source of low frequency noise, cavitation may impose distortions in the flow pattern that might lead to LFN phenomena. Noise related to turbulence is broadband as well, possibly in the lower frequency range (Birajdar et al., 2009).

If pumps are used outside of their design conditions, a variety of phenomena might occur. Examples are backflow, rotating stall, or water hammer. Each of these phenomena may lead to the emission of LFN. Backflow occurs when the inlet flow is less than the design flow, leading to recirculation of the fluid. If flow rates are around 60% of the design flow rate or lower, sound power increases mainly at frequencies close to the rotating frequency. Amplitudes intensify as the flow diminishes (Si et al., 2013). Extra care must be taken to provide the required suction head if the fluid contains dissolved gasses (Tatro, 1986). This is the case for geothermal energy applications. Water hammer relates to the sudden force on a pump after a sudden opening or closing of the valves, or a sudden starting or stopping of a pump. Pressure surges at the speed of sound travel through the system. These waves go back and forth reflecting from the valve and tank until all energy is dissipated. Interaction with pressure pulsations coming from the pump can damp but also amplify this effect (Ismaier & Schlücker, 2009). Water hammer is a transient event.
Rotating stall is a disturbance of the fluid rotating at a fraction of the pump speed in the circumferential direction along the blades. It induces strong vibrations and noise.

Mechanical vibrations
Vibrations of the pump housing resulting from mechanical processes may be radiated as noise. Important excitation forces are rotor imbalance and pump wear (Birajdar et al., 2009). Both are important reasons for vibrations in pipelines and other mechanical coupling. Transfer of vibrations to pipelines can be reduced by flexible hoses or expansion joints (Baars, 2007). Vibrations resulting from imbalance forces have a fundamental frequency at the rotational speed, which amplitude varies proportional to the square of the rotational speed (Birajdar et al., 2009). Related noise spectra are therefore low frequency and tonal. Other possible mechanical causes of vibrations are pump and motor misalignment, eccentricity, or a bent shaft. These induce vibrations at 1x, 2x or 3x the rotational speed.

3.2.5 Gas turbines

Turbine engines are used in the mining industry to drive centrifugal compressors. Normally they are not used for reciprocating compressors. Industrial turbines operate in the 6000 – 8000 rpm range. Alternatively, aircraft-derivative types of turbines may be utilized which can have rpms between 8000 and 30.000 rpm and usually require a speed-reducing gearbox (Ecology and Environment Incorporated, 1992). Gas turbines consist of an air compressor, the combustion chamber, turbine section and the air intake and outlet. They are generally fueled with natural gas, especially if this is already available on site.

Most relevant for the emission of LFN is the exhaust outlet of the turbine. Noise emitted from the exhaust is tonal in nature and dominated by the lower frequencies (Hessler, 2005; Howell & Weatherilt, 1993). Gas turbines usually have silencers in the inlet and outlets, but relevant levels of LFN may still be emitted from the exhaust. As the exhaust noise does not propagate through piping but is emitted directly into the environment, gas turbines do not excite vibrational and acoustic modes of connected parts as much as the compressors they drive. Therefore, turbine noise is emitted relatively locally.

Multiple sources add to the complex noise spectrum of the turbine exhaust (Kudernatsch, 2000). Which source contributes the most, does not follow directly from literature and may differ from time to time depending on the circumstances. The main contributors to the lower frequency components entering the exhaust stack are combustion instabilities and jet noise. Combustion pulsations lead to narrow band low frequency peaks in the noise spectrum (Hessler, 2005). However, even in the absence of such pulsations low frequency levels characterize the spectrum (Kudernatsch, 2000). According to (Kroeff, 2005), the most important aerodynamic contributor to the low frequency noise is the jet flow from the duct exit. According to (Cumpsty, 1975), acoustic power has been related to thermo-acoustic coupling due to temperature fluctuations in the combustor. A more uniform combustion behavior with stable flame configuration has shown to significantly reduce exhaust noise (Sieminski & Schneider, 1987). In addition, Kudernatch showed both theoretically and experimentally that tonal behavior is a modal function of exhaust geometry rather than just the combustion source and that tones depend on exhaust gas temperature and stack geometry (Kudernatsch, 2000). For tall stacks of 30 meters, this can be as low as 3 Hz.

Mufflers are used in the exhaust duct to attenuate the noise. Both dissipative and reactive mufflers exist. Dissipative silencer systems achieve the necessary attenuation at very large baffle thicknesses which is costly and causes pressure drop (Kudernatsch, 2000). Reactive mufflers may be effective at lower frequencies, however costly extended compartment lengths are needed to attenuate sufficiently. For peaks around 10 Hz, mufflers of 7 meters long are needed (Kroeff, 2005).

3.2.6 Noise reduction measures

Possible measures that can be taken to prevent the emission of LFN from rotating equipment include the following:

- Tuned resonance dampers (not effective in case of variable frequencies)
- Orifice plating.
- Helmholtz resonators.
- Quarter wavelength resonator mufflers.
- Under grouting of the foundation. This involves filling up openings below steel foundation baseplates to reduce vibrations.
- Dilatation of the foundation.
- Stiffening of (piping) supports
- Vibrational damping between equipment and foundation (not often used because of mechanical problems of vibrating machinery).
- Lagging on air inlet and outlet.
- Silencer in exhaust pipe. Should preferably be placed inside the enclosure as they may be important radiators of noise.
- Changes to the operating conditions to prevent excitation of vibrational or acoustic modes. Often a temporary solution.
- Reduction of the transfer of vibrations to pipelines by flexible hoses or expansion joints

In addition, equipment is often placed inside to prevent noise emission to the environment. These buildings are not typically a necessity with regards to the process or safety measures, which means they are not automatically part of the facility design and should be considered explicitly with regards to noise. Buildings should be provided with sound absorption material on inner walls and doors. Because of safety issues additional safety considerations will be in place regarding gas-detection systems, explosion hatches and ventilation systems. (Baars & Nieuwenhuizen, 2004). Because of the lightweight explosion panels, sound insulation is less effective. For all types of compressors in enclosures, inlet and outlet of mechanical ventilation systems ought to be provided with sufficient silencers, as goes for any exhaust pipes. Pipes are sometimes enclosed or insulated as well, although primarily to limit thermal losses. Noise reduction measures to prevent the radiation of noise from pipes is presented in paragraph 3.3.

3.3 The flow of gas and liquids through pipeline systems and processing facilities

3.3.1 Introduction

Pipelines are an important noise source in the mining and process industry. The flow of gas and liquids through pipelines can generate significant flow induced noise in itself, but pipelines also transport the vibrations from other noise sources, such as pumps or compressors, and can radiate these vibrations effectively as sound in the environment. Not only because the cumulative surface area of pipelines often by far exceeds the area of other radiating surfaces, but also because pipelines are widespread within a mining plant and transport pipelines penetrate closer into the living environment, leading to higher immission levels at the same sound power.

There is a widespread believe and a worldwide concern, that underground gas pipelines contribute to the complaints on LFN in the living environment. (Kohlhase, 2018; V. V. Krylov, 1997; MacPherson, n.d.; McAULIFFE et al., 1965; Van Vught M, 2018). Social media play an important role in grouping and canalizing the concerns of private citizens. But the concern about pipe related noise is serious enough that a series of scientific research projects and technical standards have been initiated over the past decades, including a GMRC (Gas Machinery Research Council) report on “compressor station piping noise” (Nored et al., 2011) a VDI (Verein Deutscher Ingenieure) directive “VDI 3733 - Noise at pipes” (VDI 3733, 1996), Reference books like “Taschenbuch der Technischen Akustik” (Mueller & Moeser, 2004) and various API (American Petroleum Institute) standards, like API 618(compressors) and API 674(pumps) (API, 2014). The issue of underground pipelines is further discussed in paragraph 3.3.4.

The two API standards highlight another issue about noise and vibration of pipelines: The primary concern of vibration and dynamic forces in pipelines is not the sound emission but the dynamic stresses that could lead to a potential fracture or fatigue failure of the construction. It should also be noted that a large proportion of the literature and papers on low frequency noise and gas pipes deal with an affiliated chapter of this failure issue, i.e. low frequency noise is also used for periodical inspection and detection of cracks, faults or leaks in pipes. For inspection reasons a pipeline is excited with sound or vibration and the response is measured. An abrupt change in the response can be an indication of (beginning) faults in the pipeline. This is also a meaningful coincidence: if people (operators or citizens) notice a sudden change in the noise emission of pipelines, it could also be an indication for structural changes and the beginning of a safety risk (Kohlhase, 2018).

Much of the attention from technical analysis and reduction measures is focused on the higher frequency region. Low frequency issues are often treated as a special case, where coincidence of a source frequency with a resonance frequency plays a role. A surprising remark was found in the VDI 3733, par 3.2 (VDI 3733, 1996), where they pay special attention to “beating”, also connected to amplitude modulation or interference. Beats do not show in the normal frequency analysis of machines but can be subjectively very disturbing. They occur due to the interference of two higher frequencies, with different, but similar frequencies. Beats occur at the mathematical difference between the two observed frequencies. An example is the operation of two equal compressors conveying on a joint pipe but having slightly different operating speeds f_1 and f_2. This will result in a periodic increase and decrease of the sound level with the beat frequency f_1-f_2.

3.3.2 Sources of sound in pipelines

There are several source mechanisms for the excitation of sound in pipelines:

1. *Turbulence:* Probably the most important and widespread source of flow induced noise is caused by turbulence. The main origin of turbulence are the sharp edges in pipes in combination with too high flow speeds. Such edges can originate from less accurate welding connections, sharp pipe bends, elbows, tee-connectors, pipe diameter changes, (measurement)flanges, valves etcetera. The noise induced by turbulent flow normally has a broad-band and stochastic nature, without a preference for a sudden frequency. Due to the response and radiation of the pipeline (see below) and the A-filter, the resulting noise spectrum however has a predominantly high frequency character (peak in the spectrum at 1000- 4000 Hz typically) (VDI 3733, 1996). The response at 125 Hz is typically 40 dB lower. The acoustic sound power of a turbulent flow is highly dependent on the speed of flow (+ 20 dB for every doubling of the speed) and to a lesser amount on the pipe diameter (+6 dB for every doubling of the pipe diameter). Consequently, a wider pipe has a lower sound power than a narrow pipe when they carry the same mass flow.

2. *Vortex shedding* is a second source of flow induced noise, where a series of regular oscillating eddies are formed downstream of an obstruction in a flowing gas or fluid. Vortices detach periodically from either side of the obstruction and form a Von Kármán vortex street (Mueller & Moeser, 2004). It typically occurs if the medium flows around a bluff (not streamlined) object. It can also happen if the main flow passes a pipe side branch with closed end and a sharp edge. In pipelines this normally occurs at a fixed, single, and relatively low frequency (10-200 Hz). If this single frequency matches with an acoustic or mechanical resonance of the obstruction, this can lead to a clear tonal noise or even the mechanical failure of the construction. The forming of vortex shedding, and its frequency is always connected to a critical speed of the flow, which depends, via the Reynolds- and Strouhal number, on the size and shape of the obstruction and the density and viscosity of the medium. Vortex shedding used to be easily overlooked in the design phase as it was hard to calculate in advance. It was one of the causes of the spectacular failure of Tacoma Narrows Bridge in 1940 (British Pathé, 2012; Voss, n.d.). With modern design software vortex shedding gets more and more attention in the engineering of bridges, skyscrapers and chimneys, but also in pipelines and process industry (Campmans, 2013, 2014). Typical examples from daily life are cables resonating in the wind, such as ropes hammering on a flagpole or a sailboat mast or overhead power lines humming in the wind.

3. *Cavitation* is a third source of flow induced noise, where vapor bubbles are formed in a fluid and then suddenly implode. This happens when local pressure in a fluid oscillates about the vapor pressure of the fluid. In pipelines this pressure change typically happens when, due to obstructions the cross area of the flow reduces and

therefor the speed increases. This often happens at valves and restriction. The resulting noise emission is clearly noticeable as a roaring, rattling or ticking sound, depending on the severity of the cavitation and the number of bubbles per unit time. A daily life example of cavitation is the sound of a water boiler, just before the water reaches boiling temperature. Cavitation is not only to be avoided for noise reasons, it also may damage the construction parts on which the implosions occur (Baars, 2007)

4. *Process instabilities* can also be responsible for the generation of Low Frequency Noise. In the above-mentioned mechanisms, the actual noise source is located in a small region or a single part of the installation: for instance, a valve, a pump, or a side branch. In case of process instabilities there are large scale oscillations of flow and pressure in a much bigger part of an installation. There can be many causes of such instabilities. Sometimes there is a feedback loop between output and input parameters. Sometimes there is an undesired transition between vapor and liquid, or an unexpected mixture of materials from a mining pit. Sometimes there is a pressure or density fall leading to nonlinear effects like chocking (reaching the maximum mass flow) etcetera. The common and relevant factor is that these instabilities may lead to low frequency noise and vibrations in the fluid or structure (typically <1 Hz) (Figure 15) (Emerson, 2018; Jaouhari et al., 2018).

5. *Affiliated machinery,* such as rotating equipment is already discussed above as a source of noise. Yet is again mentioned in this list because the noise of these machines might be efficiently transported and/or radiated by pipelines. The transportation of sound might occur either as vibrations via the pipe shell or as pulsations through the flowing gas or fluid. If such noise sources actually lead to high noise levels, depends on the effectiveness of the noise radiation mechanism. An important criterion is the location of the pipe: pipes above ground will radiate their noise as airborne sound. Pipes below ground will emit their noise as ground vibrations.

3.3.3 Pipelines above ground

Pipelines above ground are in the Dutch situation mostly only pipes, which are within or close to the facility or the industrial area. For transportation over longer distances pipelines are normally buried under ground.

The sound insulation of circular pipelines, which is relevant for flow internal noise, is high at low frequencies, decreases proportional to the third power of the frequency until a minimum at the ring frequency and then increases again at higher frequencies. The ring frequency is the frequency at which one wavelength in the shell fits in the circumference of the pipe. For steel pipes it is around 1600 Hz for a pipe with a diameter of 1 meter, and higher for smaller diameters (Cremer et al., 1973; Mueller & Moeser, 2004).
The radiation efficiency of circular pipes, which is relevant for shell vibrations, is low at low frequencies, but increases proportional with the third power of the frequency and flattens out to remain equal to 1 at high frequencies. The transition frequency f_t, between the two regions, is approximated by $f_t = 85/d$, in which d is the outer diameter of the pipe (VDI 3733, 1996). For a pipe of 1 meter the transition frequency is 85 Hz. For a pipe of 10 cm the

transition frequency is 850 Hz. Above this transition frequency there is efficient sound radiation. Below this frequency the sound radiation is less efficient. In the low frequency range also pipe breathing modes could be efficient radiators of LFN. In reality however most of low frequency sound radiation of pipelines above ground happens via bending vibrations, rather than pipe breathing modes (Kuhn & Morfey, 1976). The radiation efficiency of bending modes might be low, but their vibration level compensates amply for this. Bending modes might be effectively excited close to pipe bends or Tee-sections. For the first bending modes the boundary conditions on the pipe supports are important. These pipe supports could also transfer a significant part of the sound energy into the supports themselves, where they could contribute to the sound radiation. The calculation of pipe bending modes and supports should be part of the design phase of a plant. Also, because these bending modes could be important for structural integrity.

The attenuation of the noise level in or from the pipe versus distance is also important for the noise emission of pipelines. Within the pipe there is no attenuation due to geometrical extension because the propagation is one-dimensional. Due to pipe internal absorption and noise propagation through the pipe wall there is an acoustic energy loss, which is dependent on the frequency and the pipe diameter. At high frequencies and a small pipe (e.g., 8 kHz and 5 cm) this loss can be more than 1 dB per meter pipe length at medium frequencies (250 Hz) it is around 0,2 dB/m and at low frequencies it is not significant (VDI 3733, 1996). For the radiation from the pipe into free air, there is also a geometrical attenuation. Long pipe sections can be considered as line sources, for which there is a geometrical attenuation of 3 dB per doubling of the distance between source and receiver. Small pipe sections can be considered to be a point source, which have an attenuation of 6 dB per doubling of the distance.

3.3.4 Underground pipelines

Burying pipelines underground rather than keeping them above ground has some serious advantages with respect to noise reduction. A layer of 1 or 2 meter of soil is an extreme form of sound isolation and a surrounding of sand and soil is an effective vibration dampening treatment for steel pipes and in most case also an effective constraint to reduce bending modes in pipes. The high frequency sound emission of pipes is drastically reduced and generally of no concern anymore when taken underground. Low frequency sound emission however can remain an issue, also when buried underground.

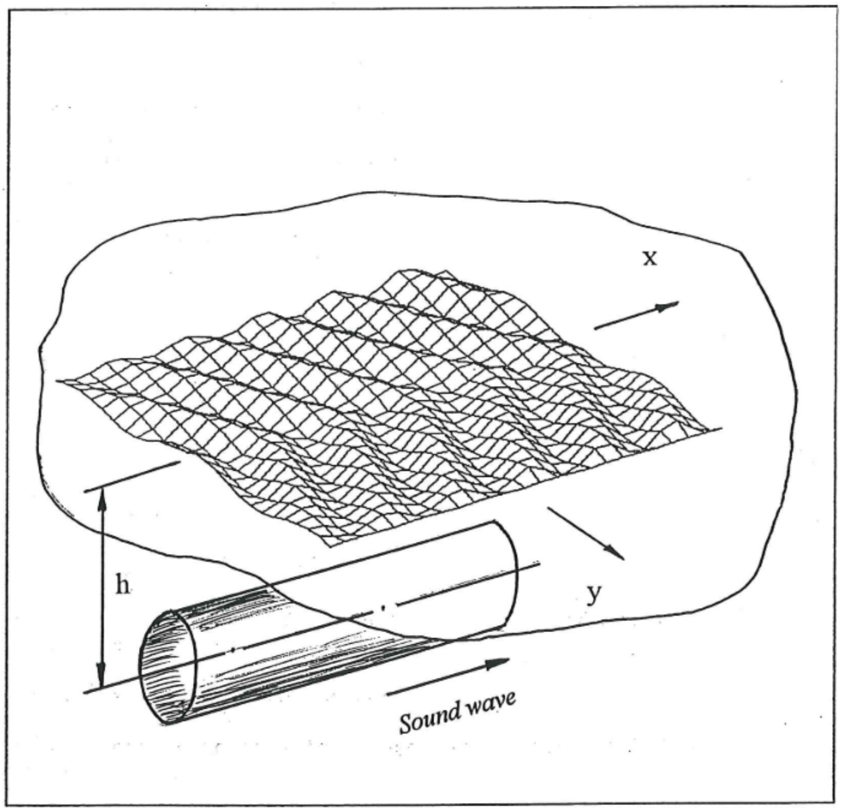


Figure 20 On the ground vibration generation mechanism associated with underground gas pipes (V. V. Krylov, 1997).

There is a widespread belief that underground pipelines are an important cause of LFN called “the hum”. The University of Loughborough have investigated the thesis that low frequency noise from underground gas pipelines could be transferred into Rayleigh surface waves in the ground and propagate into structure borne noise in the foundation of buildings (V. V. Krylov, 1995, 1997). On a theoretical basis (Figure 20), Krylov concluded that this is indeed possible if the speed of sound in the pipe is higher compared to the traveling speed of the Rayleigh surface waves in the soil. For most situation this is indeed the case. The speed of sound in methane in the pipeline is around 450 m/s and the traveling speed of Rayleigh surfaces waves depends on the rigidity of the material. In soft soil it is 30-200 m/s, in hard sand 150-450 m/s and in solid granite around 3000 m/s. The Rayleigh waves show a preferred frequency region, which is between 5 and 25 Hz for soft soil, 15-40 Hz for more rigid layers of clay, sand and gravel and above 30 Hz for stone like layers (Van Eekhout & Koopmans, 2003).

The attenuation of vibration levels over the distance from the source is dependent on the type of source (line or point source) and the type of wave (surface or spatial wave). The attenuation is quadratic with the distance or 6 dB/doubling, for a point source and spatial waves. For a line source the effect is 3 dB less than for a point source and for a surface wave the effect is 3 dB less than for a spatial wave. This means that a line source in combination with a surface wave the geometrical attenuation is 0 dB, which is logical as the connected wave front spread is one-dimensional. Added to the geometrical attenuation there is some material damping, which is highly dependent on the type of soil, the humidity etc. In most practical cases, there are several layers in the upper part of the ground, which may exhibit quite different characteristics. Reflections between the layers may play a role. Sources may vary between real point and real line source or in between. Therefore, practical experiments are difficult, and results vary a lot between researchers. Various measurements have shown attenuations between 1 and 3 dB/ distance doubling for line sources and 5-7 dB distance doubling for point sources (Bronkhorst, 2016). It must however be stressed that most these ground vibration measurements come from affiliated disciplines, like rail traffic, road traffic, driving piles or vibrating sheet piles, where the vibration levels are much higher compared to what can be expected from pipe noise.

While the transfer of pipe noise into surface Rayleigh waves seems feasible on theoretical grounds, it is hard to confirm with measurements. Measurements from the University of Loughborough could not confirm the theoretically proven transfer of pipe noise into surface Rayleigh waves. Measurements of ground vibration close to houses and close to the suspected gas pipelines did not show any vibrations above the background level, nor could they be correlated to the perceived noise levels in the house. Loughborough University have collected data of three different studies with a total of 68 complaints on Low Frequency Noise. In 12 of these 68 cases a low frequency sound could be measured in the house. In 1 case the sound could be correlated to gas industry (V. V. Krylov, 1995, 1997). A combined study on behalf of British gas and the UK Ministry of Environment found that out of 500 complaints on LFN in the UK only a few could be connected to British gas activities. In most of these cases it was unclear if this was due to airborne noise from a gas station or due to ground borne noise from underground pipes. Reduction measures were found "at the source" in the stations (Howell & Weatherilt, 1993). A recent study in the northwest of the Netherlands has investigated 33 complaints on LFN. In two cases another source was found. In three cases gas related activities were found to have a plausible relation, but more detailed investigations are still to be scheduled (Van Vught M, 2018).

In various cases complaints about LFN can be traced back to other sources than pipelines. Such sources can be house external, like road or rail traffic, agricultural machines, ships, airplanes, and industrial sites, but also house internal, like refrigerators, transformers, washing machines or ventilations systems. A special case to be mentioned here is the noise caused by the home supply of gas and water. On the internet there is a lot of material available from people complaining and service mechanics solving noise problems with pipelines within the houses. Problems with gas valves, pressure regulators, vibrating pipes or hoses, leaking toilets or water supplies for washing machines can cause humming noises, which can drive people crazy in their own home. Some of these cases are claimed to be correlated to the varying pressure on the delivery side of gas or water.

3.3.5 Reduction measures

Noise reduction measures should be incorporated in the design phase rather afterwards in problem solutions. This can avoid a lot of unsolvable problems later, reduce costs and increase efficiency of the installation (Baars, 2007). Noise reduction engineering of process installations is a specialized discipline. Some highlights are summarized here:

1. *Reduce flow noise by careful design of pipes and equipment.* The main and common factors for avoiding flow induced noise are reduction of the flow speed and avoidance of sharp edges and bends. Critical flow speeds for vortex shedding should branches should be avoided. In critical spots turbulence dampers or flow guiding

grids some help to reduce flow noise. CFD (Computer Fluid Dynamics) calculations can help to improve the flow in crucial pipe sections (Campmans, 2014; Granneman & Jansen, 2003).

2. *Reduce flow pulsations.* Pulsations from external machines, such as compressors and pumps should be reduced as much as possible and resonance in the connecting pipe system should be avoided. Various software tools have been developed to calculate pulsations in the fluid and the radiated sound from the pipes (Bruggeman, 1987; Van Der Jagt, 2007; Van Lier et al., 2006). Absorption silencers are mainly effective for high frequencies (> 500 Hz) and should be placed as close as possible to the source of pulsations. Reflection silencers are mainly effective for low frequencies (<500 Hz) and should be tuned in place and shape on the desired attenuation, which can be dependent on temperature, pressure, and flow. Helmholtz and ¼ lambda resonators can be tuned to effectively mute a single frequency. A series of resonators behind each other can cover a broader (low) frequency range. Combined or more complex silencers can cover a wide frequency range but can have the disadvantage of a high-pressure loss or even the generation of self-induced flow noise. Reflection dampers are therefor always tuned for the job, while absorption dampers are more general-purpose products from the shelf. Pulsation reduction is also important for structural integrity or energy efficiency of the process; and might be the primary reason to investigate these.

3. *Reduce bending mode excitation and radiation.* Bending modes should be calculated (eg with FEM analysis) and detuned from the main pulsation frequencies. This can be done by tuning the pipe diameters and lengths and reconsidering the amount and places of pipe supports. The radius of pipe bends should be reconsidered as they can reduce excitation of bending modes.

4. *Insulation.* Pipe insulation for noise reasons is mainly effective at higher frequencies (> 250 Hz) and can even increase the noise emission at lower frequencies, because of the mass-spring resonance in the insulation material and the increased diameter and area of the covered pipe. Flexible pipe connectors can be used to decouple the following pipe work from structure borne noise in the upstream pipe section. Softer pipe supports can be used to insulate the supporting beams from vibrations in the pipe and to avoid sound radiation from the supports (Schirmacher & Baars, 2008).

3.4 Industrial furnaces and boilers

3.4.1 Introduction

In the mining industry furnaces and boilers provide heat and steam for several applications. In the natural gas extraction sector, furnaces, also referred to as fired heaters, supply heat for the dehydration process of natural gas. In this process heat is needed to regenerate the absorbing agent silica gel or glycol. In the mineral (salt) extraction sector, steam is produced by gas fired steam boilers, which is used to evaporate water from the brine.

In general furnaces and boilers can be a significant source of LFN. But severe problems with LFN only occur in a favorable concurrence of circumstances. Emission of LFN seems to increase with the size of the furnace or boiler. In the Dutch mining industry furnaces and boilers are often relatively small compared to similar equipment used in the process industry. The largest furnaces are situated at facilities for underground gas storage (CMEO, 1993).

3.4.2 Working principle

A typical industrial furnace consists of three major components: the firebox (radiant section), the convection section and the stack; see Figure 21). The radiant section can be a vertical cylinder with mostly one burner mounted in the floor, or rectangular with often multiple burners in the sidewalls. The furnace is fired by oil, natural gas or process off-gas (tail gas). Combustion air is drawn from the atmosphere, sometimes by natural draft, sometimes forced by a centrifugal air fan. The process fluid is passing through tubes in the heater and absorbs heat primarily by radiation in the firebox and secondarily by convection from the flue gases in the convection section. The flue gases leaving the convection section are vented to the atmosphere through the stack.

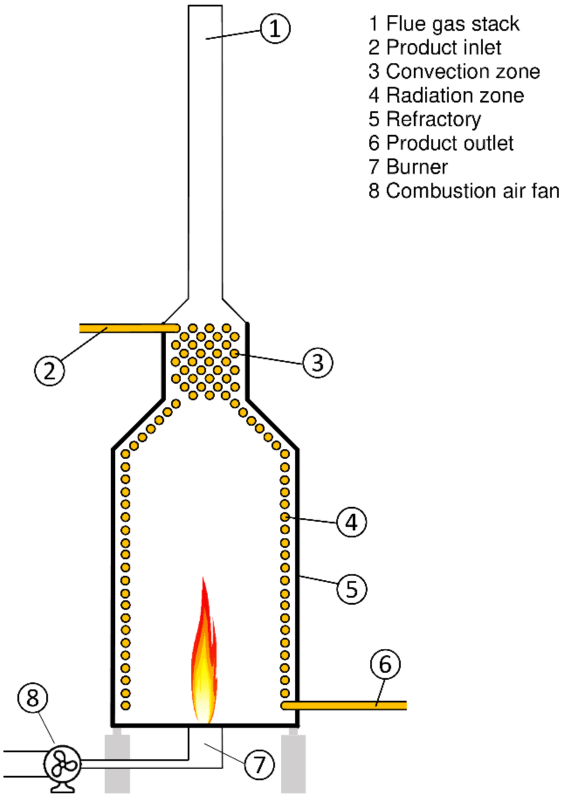


Figure 21 Schematic view of a typical industrial furnace

The most common boiler type, the fire tube boiler, consists of a horizontal cylindrical pressure vessel in which water is converted to steam; see Figure 22. Heat is provided by a burner fitted in one end of the cylinder and channeled through a series of tubes across the vessels. As with furnaces, combustion air is supplied by a combustion air fan or by natural draft. Flue gases are discharged into the atmosphere through the stack. Sometimes the waste heat of the flue gas is recovered by an economizer to further improve efficiency.

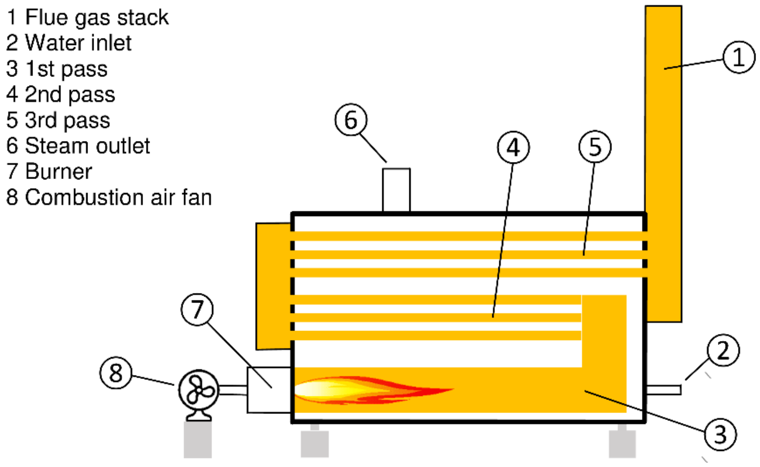


Figure 22 Schematic view of a boiler

3.4.3 Emission of LFN

Most important sources of LFN are the burners and the combustion air fan (Baars, 2007). Burners emit jet noise as well as combustion noise. Jet noise is mainly generated by the flow of the fuel gas out of the burner nozzle. Combustion noise is caused by the turbulent combustion of fuel. The noise is typically broadband. However, since the noise is radiated in a confined space (cavity), the noise spectrum generally contains tonal components that originate from the internal dimensions of the air ducts, firebox, and stack (acoustic modes).

Most noise from furnaces and boilers is radiated through the stack mouth. Cylindrically shaped furnaces and boilers are stiff and heavily insulated, hence the walls hardly contribute to noise emission (Baars, 2007). In contrast, the contribution of rectangular furnaces, especially the relatively thin-walled convection section, can be significant. With natural draft furnaces, noise can leak directly through to the air intake. These furnaces and boilers are to be fitted with a splitter silencer.

Although burner noise originates as broadband noise, the noise emitted to the environment has a significant low frequency character. Partly this is because the wavelengths of the tones resulting from acoustic modes from the interior dimensions are relatively long. Another reason for the low frequency character is because higher frequencies are attenuated by inlet silencers, furnace walls with thermal insulation, internal damping (e.g., by finned tubes in the convection section) and directivity of the stack. Boilers are usually accommodated in boiler houses, which reduced high frequency noise but has little effect on LFN. For spatial planning and environmental impact studies noise emission is usually calculated with regression formulas (Mueller & Moeser, 2004)

$L_{WA} = 83 + 10 \log (N_0/1\ \mathrm{MW})\ \mathrm{dB(A)}$

N_0 nominal thermal in power in MW, $0{,}1\ \mathrm{MW} < N_0 < 5\ \mathrm{MW}$

The sound spectrum is highly dependent on the equipment used but is usually dominated by frequency bands lower than 250 Hz.

3.4.4 Prediction of burner noise

For the prediction of burner noise, most burner suppliers rely on historical project data as well as computational tools. Although progress has been made in this area, combustion noise is still hard to estimate (Candel et al., 2009).

3.4.5 Thermoacoustic vibrations

Sometimes, industrial boilers and furnaces suffer very strong low-frequency vibrations called rumble. These vibrations are generated by dynamic feedback between the combustion process and acoustic modes in the cavities of the firebox or adjacent ducts (Helmholtz or standing waves). This is the case when synchronized phasing occurs between combustion rate fluctuations (instabilities, pulsations) and pressure fluctuations associated with the acoustic modes. Thermoacoustic vibrations are often accompanied by flickering of the flame and adverse effects like loss of thermal power, increase of NOx emissions and emission LFN noise. The amplitude of LFN is much higher than “normal” burner noise. Moreover, vibrations can damage the structure of the furnace or boiler and jeopardize the reliability of the equipment. Therefore, thermoacoustic vibrations need to be addressed immediately when they arise.

Sometimes a particular furnace may suffer thermoacoustic vibrations, while a second, seemingly an exact copy, does not. Small differences in process parameters or the layout of ductwork determines whether thermoacoustic vibrations occur. When thermoacoustic vibrations arise, typically the first attempt to solve the problem is by trial and error. Changes in the air register settings or changing the air flow of the combustion air fan can make the rumble disappear. However, it is often not possible to find a suitable process window without compromising performance and without permitting higher harmful emissions. In that case, root cause analysis is required to find a durable solution. Diagnostic testing is done with hot gas probes (Baade & Tomarchio, 2008) and multichannel measurements (Flynn et al., 2017).

In 2020 UT and TUE have started a research program on thermoacoustic vibrations. The research, called DYNAF, will run for four years (Twente, 2020). The goal of the research is to develop Computational fluid dynamics (CFD) modelling to predict thermoacoustic vibrations. To validate the models a high temperature ultrasonic temperature probe will be developed.

3.4.6 Commissioning of furnaces and boilers

During commissioning of furnaces and boilers, burner settings are optimized to meet specifications regarding performance, efficiency, and emissions. This also takes place when the equipment is modified due to stricter NOx requirements or because of the conversion from natural gas to hydrogen as fuel gas. The optimal burner setting is a trade-off between performance, efficiency, and emission, where noise and vibrations are not always considered. Small changes in the settings can cause significant differences in noise emission. Because most sound is radiated through the stack, this is not always noticed by the operators. Therefore, it is important to monitor sound and vibrations while in the process of optimizing burner settings.

3.4.7 Recent developments

In the recent past, the Dutch NOx requirements for combustion plants have been tightened. In some cases, this has led to adjustment of the burner settings. Reduction of NOx is usually achieved by extending the flame length. However, this can cause unstable flame behavior and subsequent generation of higher LFN levels.

Within the context of the transition from hydrocarbon fuels to sustainable solutions, some furnaces and boilers will be converted to be (co-)fired by biofuels or hydrogen. This involves replacement of the burners and readjustment of the settings. LFN should be considered during recommissioning of the equipment.

Due to the rapid advance of wind turbines and solar parks a surplus of electricity may be anticipated on a regular basis. For this reason, more and more electrode boilers are being put into use. This equipment type is not associated with emission of LFN. When an electrode boiler is available the existing gas-fired boiler may be decommissioned or work at a lower capacity, reducing LFN.

3.4.8 LFN reducing measures

Depending on the origin, LFN emissions from furnaces and boilers can be reduced with the following measures:

- Installing suction and discharge silencers for the combustion fans, tuned to LFN.
- Preventing sharp curves in the combustion air ducts.
- Preventing standing waves in the combustion air ducts.
- Preventing branches in the ductwork with a closed end that can act as a ½ lambda resonator.
- Limiting the flow velocity of the fuel gas out of the burner nozzle.
- Applying multiple burners instead of one large burner.
- Selecting low-noise burners.
- Reducing combustion noise by application of multi-stage air or multistage fuel injection.
- Reducing jet noise by using multiple gas orifices instead of one large nozzle.
- Covering the furnace interior or combustion chamber with noise-damping insulation material.
- Placing a checkered wall in the furnace interior to prevent standing waves.
- Preventing coincidence of acoustic resonances and structural resonances.
- Providing the stack with a suitable resonant type of silencer (works only for a small frequency range).

3.5 Man-induced earthquakes

Earthquakes result from to the sudden release of energy in the subsurface. Earthquakes generate seismic waves that can be felt on the Earth surface. The events can occur naturally but can also be induced. In the Netherlands, both types of seismic events occur and are monitored with a national seismic network (KNMI, 1993):

1. The natural occurring earthquakes are caused by a sudden movement along natural fault lines deep in the Earth’s crust. This type mainly occurs in the southeast of the Netherlands in the province of Limburg.

2. Induced earthquakes are mainly caused by gas extraction. When natural gas is extracted from the porous sandstone layer, the subsurface contracts unevenly. This can cause earthquakes and surface vibrations, with most of the spectral content in a frequency band between 1-10 Hz. These types of earthquakes occur mainly in the northeast of the Netherlands, in the province of Groningen and to a lesser extent in the northwest (Dost et al., 2017)

As the potential of geothermal energy as a sustainable energy source has led to an increased interest, research has been carried out to study induced seismicity from geothermal exploration. In such evaluations it is important to consider the geological situation near the geothermal system. From a review study of induced seismicity from such systems worldwide (Buijze et al., 2020), it was concluded that seismicity is unlikely for geothermal injection wells (doublets) that circulate fluids through relatively shallow, porous sedimentary aquifers. The authors note that it is more likely that such events could occur due to stimulations or circulations in or near competent, fractured, basement rocks. In the province of Limburg, the Netherlands, two geothermal production plants have suspended operations since the occurrence of seismic events in 2018 even though the nature of the events remain uncertain due to the sparsity of the monitoring network (Buijze et al., 2020; Spetzler et al., 2018). In the design of geothermal systems, seismic risk and hazard analysis is part of the evaluation for a production license (Geothermie Nederland, 2021).

Both induced and naturally occurring earthquakes can generate acoustic waves in the atmosphere, both in the infrasonic (Donn et al., 1964) and audible (Hill et al., 1976) frequency ranges. Most of the scientific work on earthquake sounds has focused on naturally occurring earthquakes because of the availability of audio records of such events. However, the knowledge built from studying naturally occurring earthquakes has proven to be useful in the study of induced earthquakes. A recent study by (Lamb et al., 2021) provides evidence that induced geothermal earthquakes in Finland with small to moderate magnitudes on the order of 1.5-2 (local magnitude scale) can generate observable acoustic waves with spectral content up to at least 40 Hz (Figure 23).

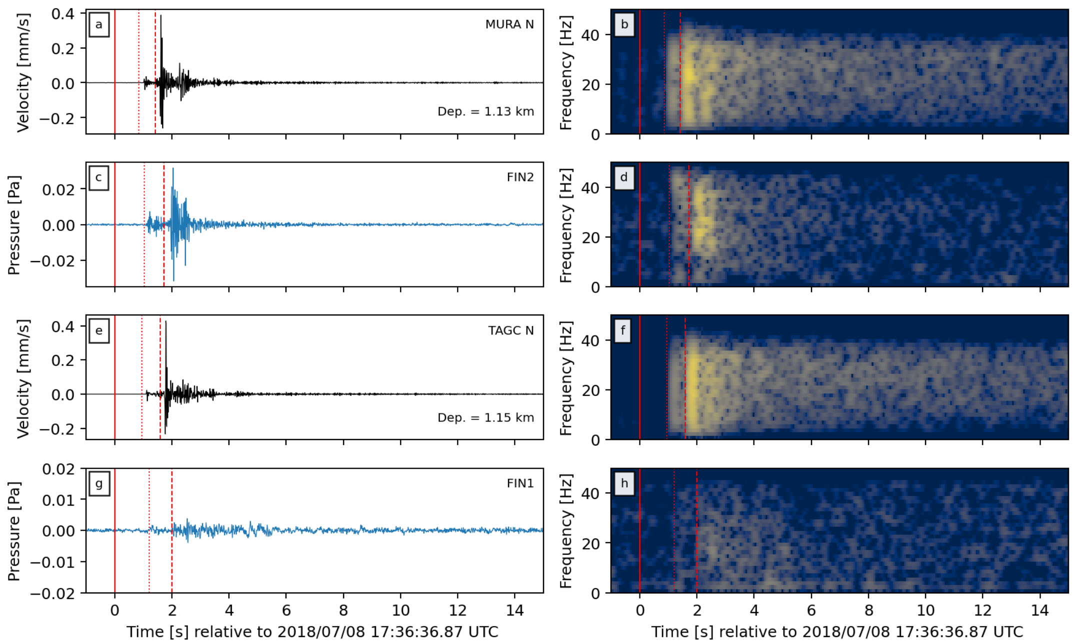


Figure 23 Co-located detection of seismic and acoustic energy following a Mw 1.86 geothermally induced earthquake in Finland. Coupled P- and SV- waves with spectral content up to 40 Hz are detected. Figure from (Lamb et al., 2021).

The coupling of seismic energy with acoustic energy can occur due to various mechanisms. The generation of acoustic waves occurs due to the continuity of pressure and vertical motion at the interface between the solid Earth and the atmosphere. It has been shown both theoretically (Averbuch et al., 2020; Godin, 2011) and empirically (L. G. Evers et al., 2014) that coupling occurs for both (P- and SV-type) body waves and surface waves. Surface waves couple readily to the atmosphere as the wave spectrum includes low phase velocities that are vertically evanescent in the solid earth but can propagate in the atmosphere.

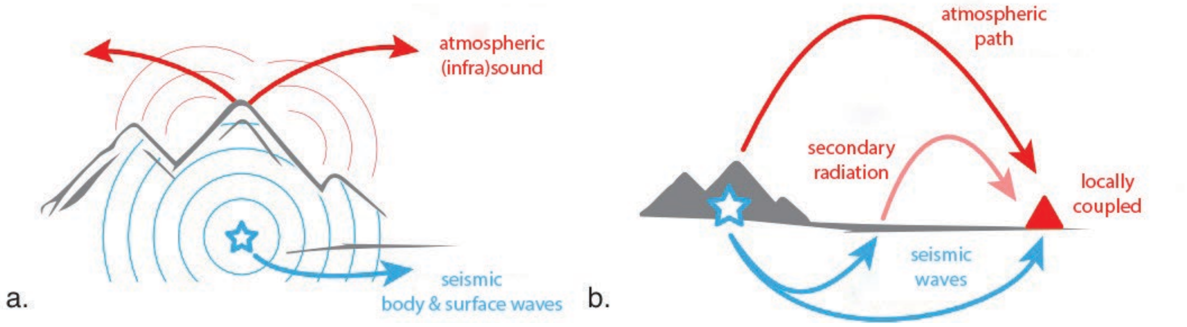


Figure 24 Conversion of seismic energy to atmospheric sound along various paths between source (star) and receiver (triangle).

Mapping of earthquake sounds has led to the identification of three source regions where seismic energy may couple into the atmosphere as an acoustic wave (as depicted in Figure 24):

1. Locally coupled: the seismic wave couples to the atmosphere directly below the acoustic sensor (Lamb et al., 2021). In the observation of this wave, care must be taken that the acoustic sensor has negligible seismic response.

2. Epicentral region: most of the seismic energy couples to the atmosphere directly above the epicenter.

3. Secondary sources due to interaction of seismic waves with steep terrain and/or sedimentary basins. The sound appears to originate away from the epicenter (Shahar Shani-Kadmiel et al., 2018; Young & Greene, 1982).

The detection of these signal types is strongly dependent on the earthquake source spectrum, the local noise levels at the acoustic station as well as propagation conditions to the remote station, both through the solid earth and the atmosphere (Section 2.4). Given the relatively complex character of the LFN field associated with earthquakes, characterization of such coupled waves benefits from the use of acoustic arrays (Section 2.3) and the deployment of co-located seismometers (i.e., seismo-acoustic measurement site).

Studies that focus on earthquake sound typically make use of joint observations of both the seismic and acoustic wavefield, by using a co-located seismometer with a LF sound sensor. Comparison of seismic and acoustic spectra shows cross-coherency up to the low-frequency audible band, in some cases 70 Hz (Sylvander et al., 2007). While the transmitted body waves (P- and SV type) generally show a broadband character, the transmitted surface waves sometimes reveal resonant frequencies at infrasonic frequencies, possibly due to interaction of the seismic surface wave with shallow geologic structure.

Witness reports (Tosi et al., 2012) have provided insight into the characteristics of perceived sound of earthquakes. It follows that sound is often heard before shaking is felt. The audible signal can be explained as the P-wave, which arrives first. Earthquake sounds are perceived significantly different inside and away from man-made structures. In the open-air, sounds range from (distant) thunder to the rushing of wind. Inside buildings, sounds are more complex due to the interaction with the building itself (Hill et al., 1976). Typical witness reports include descriptions of (multiple) booms or explosions, rumbling sounds and/or a combination of both. As part of the seismic monitoring, KNMI[5] collects such reports routinely for earthquakes that occur in the Netherlands.

An Italian study on the audibility of shallower earthquakes suggests that the audibility of earthquakes is proportional to the logarithm of the epicentral distance and linearly dependent on earthquake magnitude (Tosi et al., 2012). Moreover, the audibility was found to increase with increasing earthquake intensity, suggesting a role for acoustic signals in the earthquake intensity assessment. Shani-Kadmiel et al., 2021 derived acoustic intensity maps from remote infrasound observations following the 2010 Haiti earthquake. The acoustic intensity map corresponds qualitatively to ShakeMaps that map the Peak Ground Acceleration (PGA) or Velocity (PGV) based on seismic data and a ground motion prediction equation. In the Netherlands, ShakeMaps are computed[6] for earthquakes in Groningen with a magnitude larger than local magnitude 2.0.

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[5] See: https://www.knmi.nl/nederland-nu/seismologie/aardbevingen/melden

[6] See http://rdsa.knmi.nl/opencms/nl-rrsm and https://www.knmi.nl/nederland-nu/seismologie/shakemaps-archief

3.6 Discussion

Whereas the presented sources can by themselves lead to emission of LFN, from this study we conclude that in most cases where LFN presents a problem, a coincidence of circumstances has led to a particularly efficient radiation of LFN from the plant. For example: emission from a fan stack whose resonance frequency corresponds to the blade passing frequency of the fan. Here, an efficient LFN radiator is created due to a fortuitous tuning of several factors: the rotational speed of the fan, the geometry of obstacles in the vicinity of the blades and the dimensions, material, and construction of the stack. Such examples are typical for LFN problems because "standard" generation processes are usually considered in the design stage of a mining facility and are solved beforehand, using standard mitigation measures such as orifice plates and enclosures (Simons S. et. al., 2019). Not least because pressure variations may lead to acoustically induced fatigue. The same coincidence issue may apply for the propagation and emission part of LFN generation. An acceptable emission level can be amplified in time or space by, for instance, a temperature inversion in the atmosphere or a standing wave in a receiver room and lead to local or temporary LFN complaints. This is further discussed in Section 3.3. A special case is the propagation of LFN through underground pipelines. On theoretical grounds it seems feasible that such noise can be transferred efficiently into Rayleigh surface waves in the ground and and propagate into structure borne noise in the foundation of buildings. In practice it is however hard to confirm with measurements that this mechanism indeed exists and could be responsible for some of the complaints in the environment.

As a result of this coincidental nature, measures to solve LFN problems are often customized, and no standardized or routine procedures exist. However, based on the input of experts and literature, we provide an overview of common (concurrences of) circumstances leading to relevant emission of LFN, including prediction methods and possible measures. In the example of the fan above: measures could be taken to eliminate obstacles, adjustments could be made to the rotational frequency of the fan (if variable), the entire fan could be replaced by a low noise model with optimized blade profiles, or the vent stack could be stiffened. Which of these solutions is most adequate in a specific situation and facility, depends on many factors including process requirements, budget, and constructional factors. Within the project report, we discuss guidelines that facilitate the determination process.

A trend that could complicate matters, are the increasingly stringent requirement on NOx emission (Scheele et. al, 2006). This has an impact on LFN problems firstly because a trade-off might be needed between low noise and low NOx emissions (Self, 2018). Such trade-offs have been found to complicate reducing noise resulting from burner instabilities of industrial burners, for example. Secondly, the resulting electrification of mining equipment leads to new possible sources of LFN, such as exciters of electromotors and RC filters in the filter yard (Vijayraghavan, 1999). Of course, these electrical installations replace other LFN producing equipment such as gas turbines. This may lead to a shift in noise emission as well as to a change in the emission spectrum. The net effect on LFN emission is currently unclear. Another trend is a shift in the use of gas storage and transportation facilities. It is possible that increasing amounts of underground gas storage sites might in the future be used for CO2 storage. Furthermore, the gas transportation network might be used for transportation and/or storage of hydrogen, either through a mixture of hydrogen to natural gas or through a separate piping system. Because of the different characteristics of hydrogen, such as mass and speed of sound, this could lead to the deployment of different equipment types. For example, different types of compressors and silencers might be needed.

In the process of commissioning a mining facility, the original equipment manufacturers (OEM) are given design specifications specifying maximum noise levels from their equipment. Manufacturers provide noise specifications showing compliance to the specifications. However, those noise levels are related solely to the machine itself and do not take into account noise radiation from other components such as pipes and steel structures. The actual noise emission is therefore typically much higher than expected based on the OEM specs (Nored et al., 2011). The fact that noise is radiated away from the source results in an ambiguity when it comes to responsibilities. Suppliers are generally not accountable for noise emission outside of the equipment boundaries. And suppliers of pipelines and supports cannot be held responsible for noise emission from the pipe system if it results from specific frequency content and amplitudes related to the rotating equipment. To prevent problems after commissioning and subsequent costs to solve noise and vibrational issues, the emission of noise and vibrations at the end-parts of machinery parts should be included in specifications and contracts (Baars, 2007).

4 Human perception of LFN, its health effects and societal response

4.1 Introduction

Noise annoyance and complaints about various health effects due to LFN have been present for years. The number of people reporting LFN is currently rising. Additionally, the concern about potential health effects is growing, also for people who are not annoyed at present times but are afraid that future changes (for instance by placement of heat pumps and/or air conditioning) may expose them to LFN.

A complicating factor is that there are cases in which people experience LFN, while LFN cannot be detected. Roughly three scenarios can be distinguished:

- LFN can be detected, and a source can be found
- LFN can be detected but a source cannot be identified or taken away.
- No LFN can be detected, either due to LFN not being present or due to characteristics of the sound level meters.

Although in all three situations people can suffer quite severely, in the last two situations no noise mitigation solution can be found, and other strategies will have to be considered.

In this chapter, health effects including annoyance and sleep disturbance will be addressed, that are associated with, but are not necessarily caused by LFN. This section is followed by an explanation of co-determinants: non-acoustic factors that affect annoyance. These co-determinants can be a factor with or without sound being present. Additionally, several psycho-acoustic effects are discussed for which the potential role in the perception of LFN could be investigated.

It should be noted that the discussion of the topics in this chapter is generic and not specific to LFN sources that are relevant to the mining industry (e.g., as discussed Chapter 3), since there is a lack of research in this field. As such, this also motivates further research with a particular focus on mining activities.

4.2 Prevalence and health effects

In this paragraph health effects of noise in general and LFN in particular will be addressed. It is important to note that annoyance and sleep disturbance are seen as health effects by the WHO (WHO, 2011). We will treat these effects similarly.

Most knowledge of health effects from noise exposure considers noise in general, thus taking all sound frequencies into account. Noise in general is known to cause (high) annoyance, sleep disturbance, cardiovascular effects, cognitive effects (diminished reading abilities in children) and possibly metabolic effects, such as diabetes (Dzhambov, 2015; Zare Sakhvidi et al., 2018). Not all people are equally susceptible to these effects. Co-determinants (often called non-acoustical factors) are also of influence (section 4.3).

4.2.1 Prevalence: Randomized controlled research versus complaints

There are roughly two ways to address the prevalence of effects of an environmental stressor. One way is to study trends in time: the number of filed reports in a given time period. The other is by randomly selecting a number of people and asking them to participate in research, for instance by filling out a questionnaire or by taking part in panel discussions on the topic. Both methods have their pros and cons, and both have been used in the past years to estimate the prevalence of annoyance and other health effects in relation to LFN-exposure.

4.2.1.1 Research in the population – randomized controlled research

A limited number of studies have been published looking at health effects due to LFN. Baliatsas et al., (2016) performed a systematic review on health effects due to LFN. A systematic review means that all available literature was gathered and looked at using strict selection criteria. In this systematic review all papers were eligible that considered humans, measured LFN (not just reported by people) and health outcomes. Studies that dealt with occupational exposure, case studies, solely descriptive studies and previous reviews, reports, and conference proceedings were excluded. When applying these criteria to 502 potentially relevant articles, only 7 fulfilled the criteria. This is an indication that many more peer-reviewed studies are necessary to paint a full picture of the effects of LFN on health. Baliatsas et al. found a positive relation between LFN and annoyance and a potential link between LFN and sleep disturbance. Other mentioned health effects, such as headaches, concentration problems and heart palpitations were not systematically found in these seven articles. The authors have estimated that approximately 2 – 34% of the participants reported to be highly annoyed by the LFN they were exposed to. This large variation in the results is likely due to methodological issues, such as the fact that the sound sources, exposure levels, frequencies within the LFN-spectrum and the number of participants varied between the selected studies. Also, other aspects, such as tonality (tonal components vs. broad band noise), amplitude modulation (varying noise levels, whooshing) and non-acoustical factors (such as noise sensitivity, control, trust in the authorities etc.) will have varied between the selected studies. Similar results were found by van Kamp et al., 2019.

In the Netherlands, periodically a randomly selected sample of the general population of 16 years and older receives a questionnaire on the way that people view their living environment. Since 2016, LFN is a part of this questionnaire called 'Perception of the Living Environment' (In Dutch: *Onderzoek Beleving Woonomgeving (OBW)*, previously *Inventarisatie Verstoringen*). Because a substantial number of people fill in the questionnaire every time, it is possible to estimate the percentage of people that are (highly) annoyed and/or (highly) sleep disturbed by noise in general and by LFN. These studies are cross-sectional studies, which means that every participating individual is measured only once. Because people are not followed over time, it is not possible to draw any conclusions about the way that people develop or change sensitivity to specific stimuli, such as LFN. In the 2019 version of this study, it was found that approximately 3.2% of the population was highly annoyed by LFN and about 2.6% was highly sleep disturbed (van Poll et al., 2019), compared to 2% highly annoyed and 8% annoyed in 2016 (van Poll, 2016). It is important to note that these numbers were derived from self-reports. No measurements were done to confirm any exposure to LFN in the vicinity of the participants. However, it is an indication that more people experience LFN and/or humming sounds, be it caused by LFN or not.

4.2.1.2 Reports of and complaints about LFN

Another way to assess health effects attributed to LFN is to study the complaints that are reported to different organizations. When people (think they) know what causes the LFN or humming sound, they can address the problem by seeking contact with the company or organization they think is responsible. Other options in The Netherlands would be for instance to contact the municipality, Environmental Office (Omgevingsdienst), Municipal Health Service (Gemeentelijke Gezondheidsdienst, GGD), Ministry, Foundation LFN (Stichting LFG) and the Netherlands Foundation for Noise Annoyance (Nederlandse Stichting Geluidshinder, NSG).

Municipal Health Services

The Municipal Health Services (GGD's) uniformly register environmental health complaints in a national registration system (OSIRIS). LFN is one of the environmental factors included in this registration. Over the last decade, the number of health complaints related to LFN, as reported to the GGD, has risen (Figure 25). This is also the case for complaints about noise in general, though the rise is not as steep. A data entry will be made for all people phoning with questions or a complaint about (low frequency) noise. In most cases, advice will be offered to the individual making the report and no sound measurements will be done. It is therefore not possible to conclude that all LFN reports in fact relate to LFN. In the past, it was seen that people report LFN about a 200 – 800 Hz tone. These data do not allow one to conclude what percentage of people in the population as a whole are annoyed by LFN.

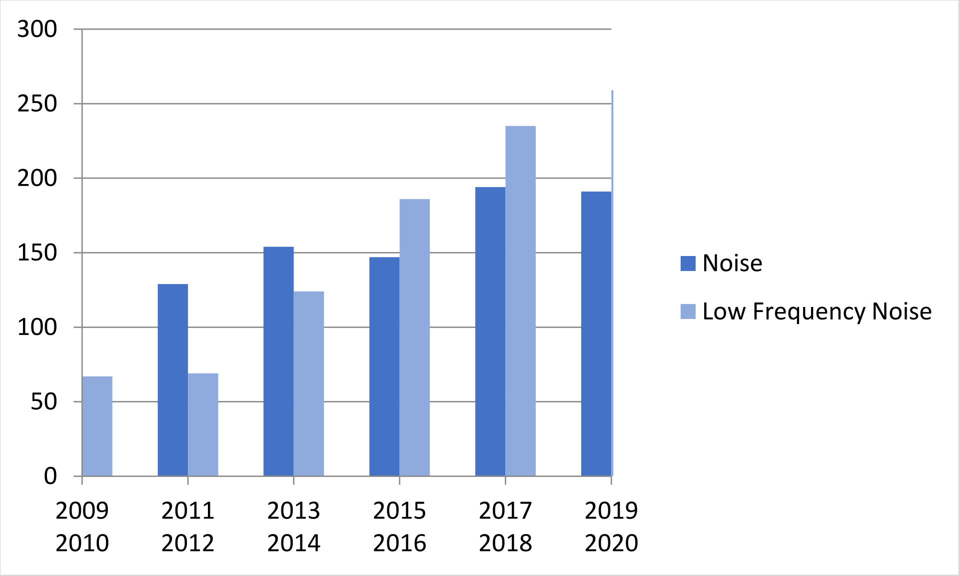

Figure 25 Number of Noise and Low Frequency Noise complaints at the Municipal Health Services (Source: (Dusseldorp, 2019) completed with data from OSIRIS/2021

LFN Foundation (Dutch: "Stichting Laagfrequent geluid")

The LFN foundation aims to inform society and people affected by LFN, acknowledge people affected by LFN, and stimulate research and sharing of knowledge. The foundation also offers a digital form to report health complaints attributed to LFN and publish the numbers online (Figure 26).

Figure 26 Number of complaints per year at the LFN foundation (source: LFg-meldingenoverzichten – laagfrequentgeluid)

Other organizations (without central registration)

In 2021, a questionnaire was sent to several other organizations, functioning as a point to report LFN (annoyance): environmental services, municipalities, and audiologists. The organizations were asked about the number of cases reported yearly and their way of dealing with the cases. A lot of differences were seen in numbers and way to deal with LFN complaints. Most of the respondents expressed the feeling that the number of reports has risen over the last 5 years. Details are described in White et al., 2021.

4.2.1.3 Attributed health effects

When reporting health complaints, people often attribute their health effects to LFN or a humming sound. In case reports health effects like headaches, memory loss, diminished concentration/performance, problems with heart and/or airways and vertigo are mentioned. These health effects of LFN have, except of annoyance, not been confirmed in scientific research.

Furthermore, a group of researchers has published several articles on the vibro-acoustic disease (VAD; among which Alves-Pereira & Castelo Branco, 2007). Most of these articles are based on occupational study and one study considering just one participant (N=1). In these articles, a relation is described between LFN and depressive thoughts, damage to connective tissue, cardiovascular disease, and epilepsy. This work is considered to be of low quality, because the articles are written in such a way that replication of the experiments (redoing them to see if the results are similar or the same) is impossible. The results (in other research designs) have not been replicated. In the medical world, VAD is not an official diagnosis.

Medical causes
Some people experience LFN as phantom sounds, i.e. they hear LFN that cannot be measured (Van den Berg, 2009). One possible diagnosis in such a case is tinnitus, but there are several other possible diagnoses. When receiving such a diagnosis, people sometimes feel as if they are not being taken seriously or that their mental well-being is put into doubt. As suggested by Van den Berg, 2009, it can be helpful to distinguish between neurological and psychological phenomena. An audiologist can assess if a hearing aid can be an effective treatment against the perceived LFN. Cognitive behavioral therapy is also mentioned as an option for people perceiving phantom sounds or people living in circumstances with measurable LFN, when the sound source can either not be found or not be adjusted or be removed. More research is needed to establish the effectiveness of cognitive behavioral therapy in case of LFN perception (present or not).

It has been suggested by Salt (2004) that swelling of the cochlea may occur due to stimulation of the tissue at extreme sound levels (i.e., using a 200 Hz tone at 115 dB SPL) This could possibly increase the sensitivity of the inner ear to LFN in particular.

4.3 The role of co-determinants (previously known as non-acoustic factors)

Co-determinants of non-acoustic factors are factors that are not part of the noise itself but do influence annoyance by noise. Co-determinants have mostly been studied in the context of noise in general.

4.3.1.1 Co-determinants for noise in general

Co-determinants are generally divided in five categories: situational, social, contextual, personal, and demographic factors.

Situational factors

Situational factors consider the environment in the neighborhood and entail factors such as: the availability of green spaces in the vicinity, quiet areas in the neighborhood and the appreciation of one's neighborhood (Dzhambov et al., 2018; Lercher, 1996; Lugten et al., 2018; van Kempen & Simon, 2019).

Social factors

Attitude towards the sound source and economic ties to the sound source are examples of social co-determinants (Leventhall, 2009; van Kempen & Simon, 2019). For instance, people working at an airport are generally less annoyed by aircraft noise than people who have no economic ties.

Contextual factors

Contextual factors entail future expectations, possibility to file a complaint and predictability of the noise (van Kempen & Simon, 2019; van Poll et al., 2008). Changes or planned changes are sometimes also considered, though this is debatable as it also involves acoustic changes. It is seen, however, that noise annoyance changes more than can be expected from an acoustical point of view: people get either considerably more or less annoyed after the situation has changed more (depending on the amount of sound going up or down). This is called an excess response (Brown & van Kamp, 2009a, 2009b, 2017).

Personal factors

Personal factors comprise a wide range of factors about how people deal with their acoustic environment. Noise sensitivity, coping abilities, feelings of (being in) control or having control over the situation and fear for the sound source are examples of personal co-determinants. Some of these co-determinants are known to correlate highly with noise annoyance, for instance noise sensitivity. Though some circumstances exist in which noise sensitivity fluctuates (depression, other mental disorders), it is mostly a stable personality trait throughout life (Stansfeld, 1992). The other personal co-determinants mentioned above are more likely to fluctuate somewhat over time.

Demographic factors

Age, gender, and social economic status (SES) are examples of demographic factors. In most studies addressing demographic factors no correlations were found between annoyance and these factors (Broër, 2006; Fields, 1993; Miedema & Vos, 1999).

4.3.2 The role of co-determinants in relation to LFN

Little is known about the relation between LFN and co-determinants. This may partly be due to the way that sound has been approached in the past decades. Though it is known that most noise sources produce LFN to some extent, research has mostly addressed effects and co-determinants of sources, not studying the effects of the LFN-spectrum separately. The number of studies addressing both LFN and co-determinants is therefore limited. The available studies are mostly studies conducted in a laboratory. Though these laboratory studies are valuable to learn about the role of co-determinants in relation to LFN, it is worth noting that the results may not (always) be generalizable to the population.

Self-reported noise sensitive people performing a task in a laboratory study were more annoyed by LFN than people who reported not to be sensitive to noise and LFN (Persson Waye et al., 2001). The sensitive group also performed somewhat less well under these circumstances. Higher cortisol levels when listening to LFN were found among self-reported sensitive participants in a similar study, indicating higher stress levels by LFN in this group (Persson Waye et al., 2002). Less clear results were found in a laboratory study using groups based on self-reported noise sensitivity scores. Annoyance when listening to different sound samples and LFN sound samples were higher in the sensitive group for some LFN-samples, but not for all (Pawlaczyk-Luszczynska et al., 2010). In this study, high sound levels were used (higher levels than can be expected in a living environment), which may have influenced the results.

No differences in annoyance by LFN were found for age and gender in the study described above using different groups (Pawlaczyk-Luszczynska et al., 2010). Similarly, no differences were found in LFN annoyance for age and work history in a study among employees of a Polish power plant (Pawłaczyk-Luszczyńska et al., 2003).

In conclusion, little is known about the role of co-determinants in relation to LFN and annoyance. There is some evidence that noise sensitivity in general and sensitivity to LFN specifically may correlate with higher annoyance levels. The evidence was not entirely consistent, however. The role of other co-determinants in relation to LFN and annoyance is yet to be determined. It is recommended that future studies take co-determinants into account.

4.4 The possible link between psycho-acoustic factors and perception of LFN

Concerning the perception of LFN, it is of interest to consider research from the field of psychoacoustics. Psychoacoustic factors may be a “missing link” between reports of LFN in cases that LFN is not measurable its frequency band (i.e., sound below 200 Hz). Several psycho-acoustic effects have been reported in the literature, albeit not specific to LFN, of which the implications deserve further research to understand the implications for LFN.
In the context of this discussion, it is important to reiterate some of the characteristics of typical LFN measurements, including frequency weighting such as described by the dB(A) and dB(C) filters (see Figure 4). These weighting factors have been designed such that they follow the non-linear sensitivity of the human ear (Figure 27). In addition, spectral averaging occurs when measurements are performed in (third) octave bands.

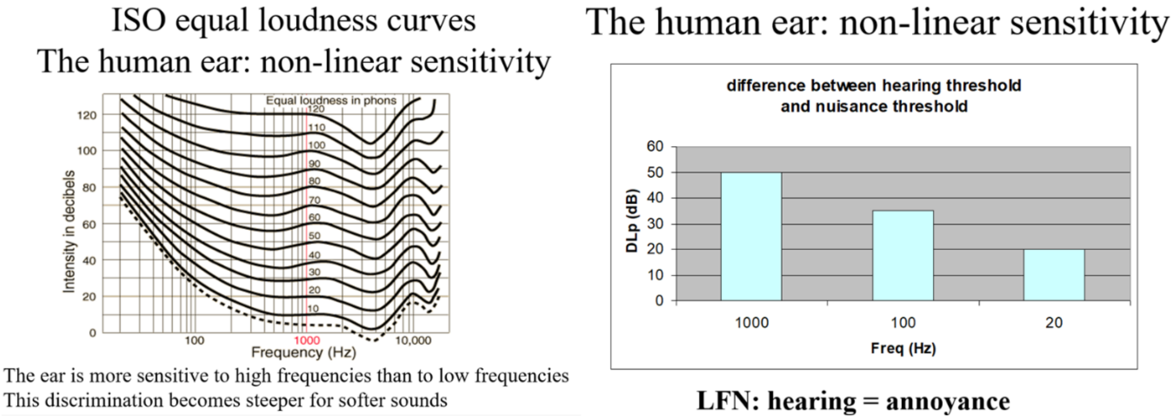

Figure 27 Non-linear sensitivity of the human ear versus frequency (graphs from(De Graaff, 2005)*, based on* (Munson, 1933)*)*

In the attempts to correlate subjective LFN complaints with objective measurements, most efforts are currently spent on finding real energetic sound contributions in the (third) octave band spectrum (e.g., Section 2.3). It must however be recognized that the subjective appraisal of sound is not only determined by the actual sound levels. A multi-disciplinary approach with medical, biological, psychological, musical scientists and therapists could be of value to improve the understanding of some people's sensitivities to LFN and noise in general.

In what follows, a discussion of psycho-acoustic effects is provided that could be of interest when studying LFN. However, it should be recognized that the role of these psycho-acoustic effects is not understood for low frequencies and more research is needed.

- Low frequency noise is often tonal (Van Lier et al., 2006). Tonal noise is assumed to be more annoying and therefore assessed more strictly by law in many European countries (Peeters & Nusselder, 2019) (e.g. with 5 dB penalty) The revision proposal of the DIN45680 norm for LFN contains a correction method for tonal sounds (Krahé, 2017). However, the assessment of tonality is not always clear nor standardized. For instance, octave band and narrowband spectral analyses may come to different conclusions.

- Fundamental frequency vs. higher harmonics. The generation of a (low frequency) tone often automatically introduces some higher harmonics of its fundamental frequency. This is well known for musical instruments, but also true for rotational machines like diesel engines and compressors. The fundamental frequency will be heard as the root note and the number and relative amplitude of the higher harmonics will determine the timbre of the sound. A difference in root note enables the audience to determine the difference between a bass and a soprano voice or between a low speed and a high-speed engine. This timbre versus root note effect may influence both the reported annoyance as well as the objective sound measurements:

- People complaining about a low frequency noise often mention a noise like a diesel engine. In many cases it is unclear if they are complaining about the fundamental frequency or about the higher harmonics.
- Different types of frequency analysis highlight different parts of the frequency spectrum and therefore emphasize either the fundamental frequency or the harmonics. FFT analysis, Cepstrum analysis, order tracking and linear weighting typically emphasize the fundamental frequency. (Third) octave band analysis and A-weighting typically emphasize the harmonics (see also Figure 18). The traditional A-weighted 1/3 octave band analysis may therefore overlook issues related to the fundamental frequency.

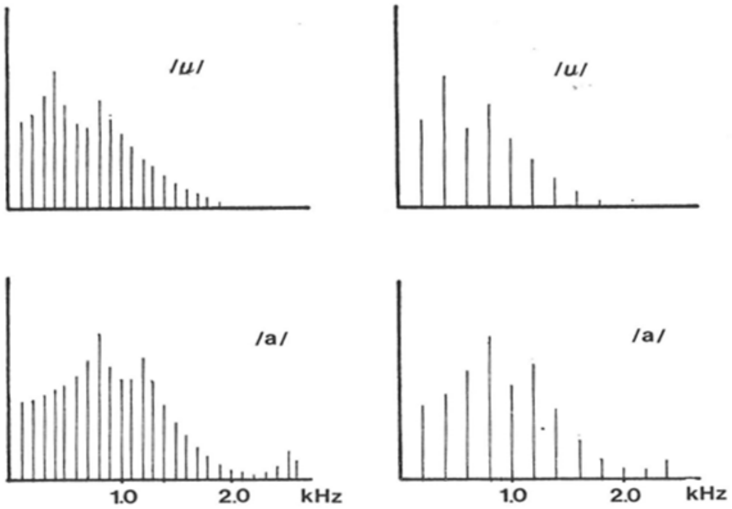

Figure 28 FFT narrow band spectra of four human sounds with two different root notes and two different timbres. Left graphs are from a male voice with fundamental frequency of 100 Hz; right graphs are from a female voice with fundamental frequency of 200 Hz. Upper graphs show the higher harmonics of a sounding /U/ (OEH); lower graphs show the higher harmonics of a sounding /A/ (graphs from (De Graaff, 2021)*)*

- Tartini tones or combination tones are the psycho-acoustic effect in which a third artificial lower tone is heard when the ears perceive two real sounding higher tones simultaneously. The effect is thought to be from the non-linear response of the middle ear (e.g., Schneider, 2018). The frequency of the combination/Tartini tone is equal to the difference of the frequencies of the two real tones. If for example two real tones are 300 and 400 Hz, the artificial Tartini tone is 100 Hz. This effect was first described in the 18th century by violinist Giuseppe Tartini, but significantly elaborated upon by acoustics founding father Hermann Helmholtz in the 19th century (Helmholtz, 1863). The effect is used by musicians for instance to tune their instrument. Pipe organs have been built using this principle to create the suggestion of low frequency bass pipes, while in reality only the 2nd and 3rd harmonic pipes were physically used. The effect of "creating the missing fundamental" is even stronger when more harmonics are physically available. If the fundamental frequency is above 20 Hz, it will be interpreted as a low frequency sound. If it is below 20 Hz, it will be perceived as beating or amplitude modulation. This psycho-acoustic phenomenon may be accountable for the perception of LFN for some people. For annoyance by low frequency noise, this effect may also be relevant. The sound spectrum of rotational machines like diesel engines contain a lot of higher harmonics of the fundamental rotational frequency (see Figure 18). In some cases, this may be due to the inner ear, or possibly the brain, perceiving these harmonics to belonging to the same low combination tone. When focusing on the LFN band only, sound level meters may not be able to quantify these harmonic relations and focus on the sound energy of the harmonics in the octave band analysis (Figure 28).

- Binaural effects: recent experiments have shown that a combination tone is also formed when two higher tones are presented to each of the ears separately with headphones. This also results in binaural beats. Both binaural beats and monaural beats are suggested to efficiently change the mood of people. Depending on their frequency, they are connected to a diverse range of effects such as reduced anxiety, improved performance and reduced stress (Engelbregt et al., 2019; López-Caballero & Escera, 2017; Orozco Perez et al., 2020; Padmanabhan et al., 2005). Binaural effects have also been suggested to improve the correlation between subjective appreciation and objective measurements, as is known from product optimization in the automotive industry.

These examples of psychoacoustics suggest that a multi-disciplinary approach to the LFN problem is necessary to obtain a broader understanding of the observations that are being made.

4.5 Complaint handling

The handling of complaints is not very standardized and often not so obvious to the public. Reports or complaints can be made at various institutions such as the municipal health services (GGD), the regional environmental services (Milieudienst/RUD/OGD) or to the licensing authorities such as Provinces or State Supervision of the Mines (SSM), or other stakeholders such as the Dutch Foundation on Low Frequency Noise (Dutch: “Stichting Laagfrequent geluid”), the Dutch Foundation on Noise pollution (NSG), but also to local doctors or hearing care professionals. Bigger companies may have a designated entry for complaints by individuals. Some of these organizations have set up a telephone hotline or website to handle complaints (e.g., https://www.dcmr.nl/overlast-door-bromtoon-laagfrequent-geluid) or have setup informative websites or brochures (e.g. https://ggdgelderlandzuid.nl/wp-content/uploads/2016/10/brochure-Ik-hoor-een-bromtoon-versie-2.pdf).

Some years ago, members of the Municipal health services (GGD) have established a provisional joint guideline on LFN (Slob et al., 2016).The LFN guideline provides help to deal with LFN complaints reported to the GGD. The measurement method described in the guideline is based on a method used by the environmental service at Rotterdam (DCMR) at that time. This method is based on (DIN45680, 1997) and determines the difference between dB(A) and dB(C) (see also 2.3.1., 2.3.5 and 4.4). Using this method, a sound meter will measure for a duration of 10 minutes. Afterwards, it is calculated if during this period, the difference between dB(C) and dB(A) exceeds 20 dB. If so, this can indicate that LFN is present, as dB(C) is more sensitive to LFN than dB(A). Further research may then be warranted. Another method is currently being discussed, as positive results are being reported. This method is based on ‘joint fact finding’: instead of considering the complete sound environment, this method focuses on the specific frequency that is causing annoyance and/or other effects. The ‘problematic’ frequency is determined by means of singing (by the annoyed person) or with the use of a sound generating app (annoyed person recognizes the annoying frequency). When the 'problematic' frequency is determined, a specific search for its source and a potential solution can then start, leaving sound by other sources unchanged.

4.6 Laws and regulations

The regulations and assessment methods on LFN are scattered. In the Netherlands two directives are sometimes considered for jurisprudence for specific locations: The NSG-curve (NSG, 1999) and the Vercammen-curve (M. L. S. Vercammen, 1989). Other countries have different regulations and assessment methods to deal with LFN (Figure 29). Both the target level and the frequency range of interest varies among the countries. It is interesting to see that the Dutch NSG curve is limited to the 20-100 Hz range, while other curves range between 8 and 250 Hz. This calls for a further standardization and a critical review of the targeted frequency range of LFN. The most referred assessment standard (DIN45680, 1997) is currently under a revision process (Krahé, 2017).

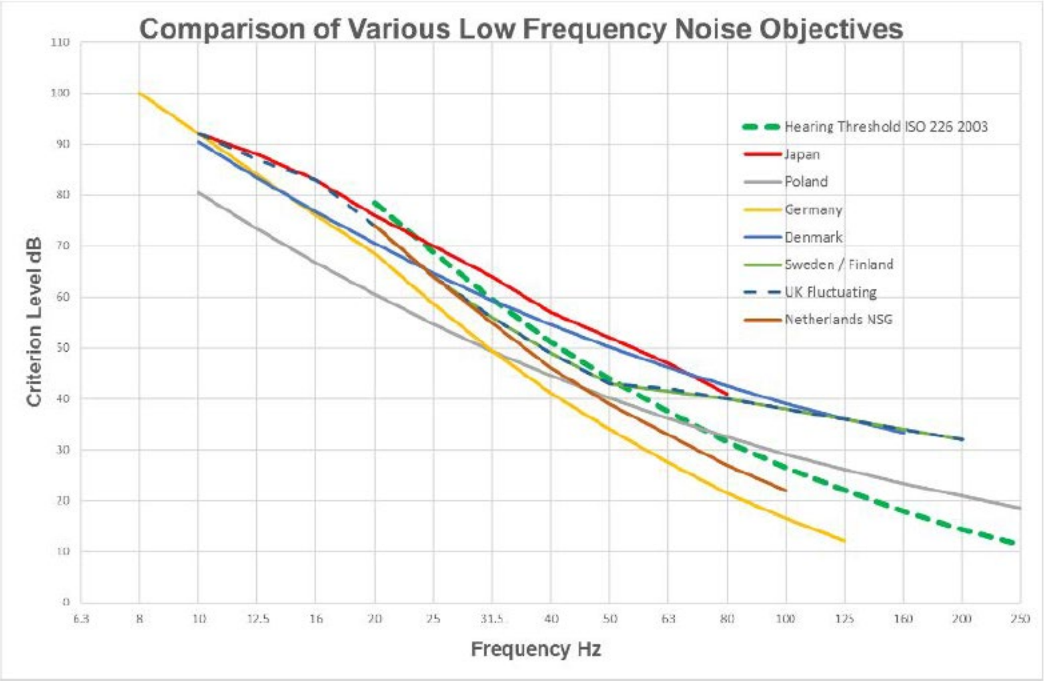

Figure 29 Various assessment curves for LFN (source: (Downey & Parnell, 2017))

In the Netherlands, the general laws on noise annoyance (*Wet Geluidhinder*, 1979; *Wet Milieubeheer*, 1993) cover the whole sound spectrum, including LFN. There is no specific legislation on LFN, nor are there any norms targeting just the low frequency spectrum. Regulations for specific locations can also be formulated by municipalities using tailor-made regulations (Dutch: "maatwerkvoorschriften"). In July 2022 the Environment and Planning Act (Dutch: "Omgevingswet") will be implemented. Expectations are that this act will ease urban and regional planning/land use planning (Dutch: "ruimtelijke ordening") for municipalities. Environmental sound will be one of the environmental exposure types that will be regulated with the Environment and Planning Act at least to some extent.

4.7 Discussion

In 2019 approximately 3.2% of the population reported to be highly annoyed by LFN (an increase of about one percent compared to 2016) and about 2.6% were highly sleep disturbed (van Poll et al., 2019). In the central registration of the Municipal Health Services and the LFN foundation, an increase is seen in the number of complaints. Since in these cases no data on the exposure to LFN is available, this does not allow for conclusions about the cause of this rising trend, nor the derivation of a dose-response relationship. However, the numbers indicate a growing concern of the topic.

More research is needed to address the relationship between exposure to LFN and health responses, such as annoyance to it, preferably also taking co-determinants such as noise sensitivity into account. This type of research is needed to help understand the possible mechanisms concerning annoyance by perceived LFN.

More focused research is also needed that considers reports of LFN and actual measurements of LFN from potential LFN sources (e.g., as discussed in Chapter 3) in the vicinity of those complaints. As the contribution of these sources to the LFN field is not well understood, it is difficult to assess individual reports. As a first step, it should always be verified if the reported tone is above or below the cut-off frequency of 20 Hz for standard audio recordings and sound measurements (Section 4.2.1.2). If measurements at lower frequencies are indeed required, such measurements should be carried out with equipment that has an adequate response for the LFN band (Section 2.2.1). It is important that the measurements are interpreted within the context of the ambient background noise (Section 2.3.5). Moreover, the transfer function of the acoustic environment (Section 2.4) and the dwelling (Section 2.5) are to be considered.

To avoid loss of information, recordings should be stored without averaging and frequency-weighting. If the possibility of an acoustic cause can be excluded, further investigations can focus on other factors, such as co-determinants, psycho-acoustical effects, or neurological phenomena.

5 Conclusions and recommendations

5.1 General discussion

The goal of this report was to address the following topics:

1. An inventory and characterisation of generated LFN from processing facilities, including equipment and the flow of gas and liquids through pipeline systems, as well as from induced earthquakes.
2. Methods on how to use technical observational systems as well as observation by citizens or models for proper assessments of current or future LFN generation and exposure to be expected.
3. An overview of potential impact of LFN and references to sound norms.

This report combines knowledge from various scientific disciplines, including acoustics, mechanical engineering, and psychology. The knowledge was obtained through literature study as well as interviews with domain experts. The various aspects of these disciplines related to LFN have been discussed and summarized in the preceding chapters. The multi-disciplinary approach that was used, has allowed for multiple perspectives of this topic, which is generally uncommon in LFN studies.

From the analyses presented in this report, it follows that the assessment of LFN from mining installations involves a large number of variables and unknowns which complicates the assessment of LFN radiation. To illustrate the complexities, a schematic depiction has been included (Figure 30).

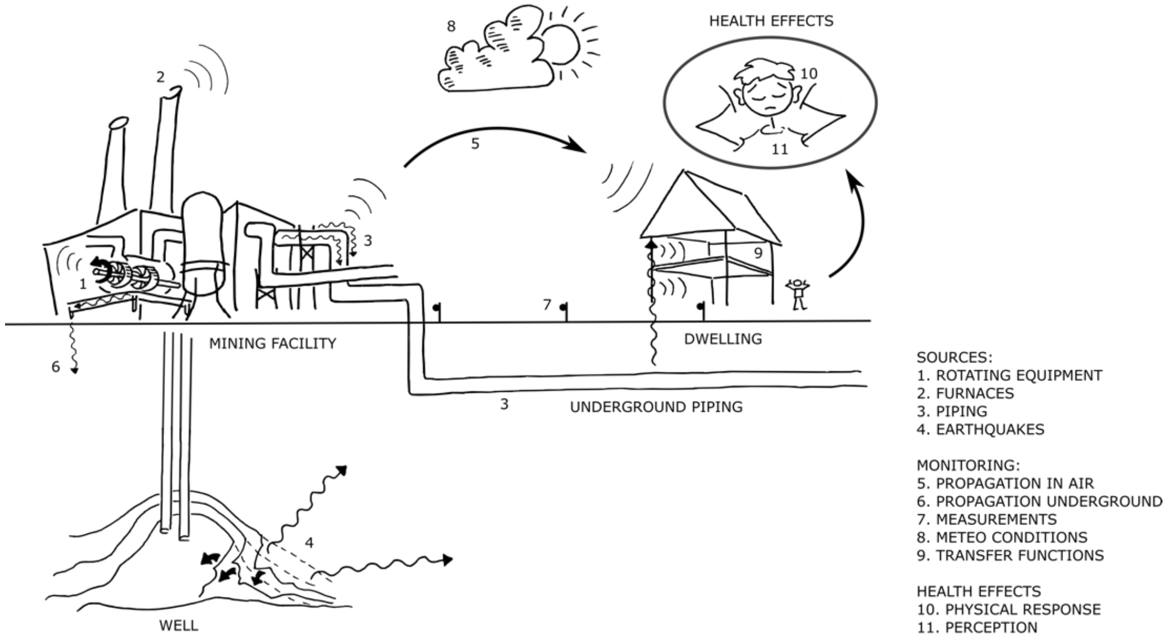

Figure 30 Various parameters that play a role in the study of LFN from mining installations. The assessment of LFN of such sources is associated with many variables and (unknown) unknowns and should be studied in conjunction.

It follows that mining installations include complex potential LFN sources that can result in generation of LFN at multiple locations, both through the air and in the subsurface. The transfer of the vibrations that can be emitted by such sources propagate through the subsurface and the atmosphere, which adds another level of complexity. Additionally, the transfer of acoustic energy into dwellings may lead to amplifications of specific frequencies, depending on the transfer function of the building. Finally, the research on perception and health effects in humans to LFN is ongoing. Epidemiological research is scarce and are not always comparable due to differences in approaches (Baliatsas et al., 2016; van Kamp et al., 2019).

Therefore, it can be concluded that the assessment of LFN from mining activities can be relatively complex and characterization may need expertise from a wide range of scientific disciplines (physical acoustics, bioacoustics, psychoacoustics, engineering acoustics, seismo-acoustics, and epidemiologists).

5.2 Conclusions

In the following subsections, conclusions are presented from the individual chapters.

5.2.1 Chapter 2: The physics of LFN: monitoring and simulating

- The low-frequency sound field consists of diverse natural and anthropogenic sources that are continuously present in the background. The complexity arises because of the presence of multiple sound sources thanks to efficient propagation conditions as well as the influence of the wind on the acoustic measurements.
- Typical sound level meters have been developed for standardized sound pressure level measurements. Typically, data is presented in (third) octave bands, following dB(A) or dB(C) weighting. The dB(C) filter has a lower-frequency cut-off at 31.5 Hz and is not appropriate for infrasound measurements as well as low-frequency audible sound below 31.5 Hz.
- In The Netherlands, noise mitigation measures in mining facilities are standard, but requirements are based on dB(A) weighted noise levels. Therefore, typical noise reducing measures are aimed on the high frequency content of the dB(A) and do not consider the lower frequencies.
- For the measurements of (near-)infrasound, specialized sensors has been developed, for which specialized calibration procedures and deployment guidelines exist.
- Recent advances in low-cost, miniature MEMS sensors are promising for LFN monitoring and can be used as mobile measurement platforms. The data quality is still compromised when compared to high-fidelity equipment.
- Sensor arrays or directional microphones are important in the detection, localization, and identification of acoustic waves, in particular at longer ranges.
- The background noise consists of wind-related pressure fluctuations and ambient acoustic noise. The background noise varies with location and time.
- Atmospheric sound propagation can be considered a linear process, which means that no lower or higher frequencies can be generated along the propagation path that are different from the source spectrum. It is possible that the distribution of the spectrum shifts to lower frequencies along the propagation path since higher frequencies attenuate more rapidly.
- The indoor sound field is strongly affected by dwellings, for which knowledge on the transfer function is needed.

5.2.2 Chapter 3: Sources of LFN

- In the Dutch mining industry, rotating equipment, pipelines and furnaces can be sources of LFN. LFN of subsystems can be reasonably well predicted, but the LFN emission of more complex systems is hard to predict. When specific problems occur in practice, it is typically due to the concurrence of certain circumstances, such as the interaction of resonances of connected structures with the fundamental frequency of a LFN source.
- Above ground pipelines often represent the largest radiating area in industrial plants and can radiate LFN originating from an affiliated source (like a compressor) through mechanical vibrations or acoustical pulsations. In such a case enclosing the actual source does not solve the problem.
- Unlike compressors and pumps, gas turbines radiate LFN mainly from the exhaust rather than transmitting acoustic and vibrational energy to connected pipes and structures.
- Rotating machinery produce pressure pulsations at frequencies corresponding to the rotational speed times the number of blades, vanes, lobes, or pistons. The noise spectra include the fundamental frequency plus harmonics. For reciprocating pumps and compressors, the resulting noise spectrum is dominated by frequencies in the LFN region. The fundamental frequency of centrifugal machinery is typically above the LFN region, because operating speeds of centrifugal machinery are higher and numbers of blades and vanes are typically larger compared to reciprocating machinery. However, low frequency components at the rotational speed are present and might excite vibrational or acoustic resonance modes in the system. In addition, unwanted phenomena such as backflow, stall and surge may lead to the emission of LFN. Furthermore, LFN might be generated if machinery is deployed outside of the operating range.
- The increasingly stringent requirement on NOx emission may have an impact on LFN problems. Firstly, because a trade-off might be needed between low noise and low NOx emissions as has been seen in the case of industrial burners. And secondly because the resulting electrification of mining equipment leads to new possible sources of LFN.
- Induced earthquakes are transient events that can be produced by mining activities, including gas extraction and geothermal exploration. These can produce observable low-frequency noise that can be heard and felt. The associated signals are experienced differently inside a dwelling.

Regarding trends:

- The production of geothermal heat as a renewable source of energy appears to be on the rise. It is expected that more geothermal energy facilities will be built in the near future, possibly in the vicinity of current geothermal facilities, where the suitability of the ground has been demonstrated. As the construction of geothermal sites becomes more common and more experience is gained within the community with regards to noise mitigation standards, it is expected that compliance with noise legislation will be tackled more efficiently and at an early stage, than was the case in some of the earlier pioneering. At the moment, facilities typically consist of one or two doublets; in the future, up to four doublets might be drilled from the same facility. This implies that slightly larger equipment will be needed, although no immense expansion of facilities is expected.

- It is possible that in the future, an increasing amount of underground gas storage sites might be used for CO2-storage. Furthermore, the gas transportation network might be used for transportation and/or storage of hydrogen, either through a mixture of hydrogen to natural gas or through a separate piping system. Because of the different characteristics of CO2 and hydrogen, such as mass and speed of sound, this could lead to the deployment of different equipment types and subsequently to changes in the potential LFN emission.

5.2.3 Chapter 4: Perception, health effects and societal responses

- Epidemiological research on LFN and health effects is scarce and studies that have taken place are not always comparable due to methodological differences. Because little epidemiological studies have been carried out in which health endpoints, such as annoyance, sleep disturbance and cardiovascular effects, and acoustic factors were both studied, there is a knowledge gap concerning the correlation between exposure and responses.
- In the attempts to correlate subjective LFN complaints with objective measurements, most efforts are currently spent on finding real energetic sound contributions in the (third) octave band spectrum. It must however be recognized that the subjective appraisal of sound is not only determined by the actual sound levels. Special cases, such as tonality, modulation, harmonics or Tartini tones, are not detected by the usual dB(C) measurements or octave band analysis, but could be an explanation of some of the LFN complaints.
- For sound in general, it is known that co-determinants (non-acoustic factors) affect the way that the sound is perceived. For LFN, a few studies have addressed the role of noise sensitivity and sensitivity for LFN specifically. Research on other co-determinants has yet to be performed.
- The regulations and assessment methods on LFN are scattered. Both the target level and the frequency range of interest varies among the countries. The most referred assessment standard (DIN45680, 1997) is currently under a revision process (Krahé, 2017). In the Netherlands two directives are sometimes considered for jurisprudence for specific locations: The NSG-curve (NSG, 1999) and the Vercammen-curve (Vercammen, 1989). This calls for a further standardization.
- A multi-disciplinary approach with medical, biological, psychological, musical scientists and therapists could be of value to improve the understanding of some people’s sensitivities to LFN and noise in general.

5.3 Recommendations

The following recommendations are made based on the research presented in this report:

5.3.1 Chapter 2: The physics of LFN: monitoring and simulating

- Acoustics research (in the fields of bioacoustics and physical acoustics) must be carried out to determine which frequency bands and processing steps are relevant in LFN work. Once our understanding of this has sufficiently progressed, this information can be used for design sound level meters for standardized, routine LFN measurements. We are not yet at this point in science that we know what type of filtration is appropriate.
- It is important to characterize the background noise spectrum to understand its variations with time. This should be done through 24/7 monitoring with ruggedized sensors that are optimized for this.
- Unwanted pressure signals due to meteorological processes become more pronounced with decreasing frequency and may influence acoustic detection. Care should be taken to minimize these effects, i.e., by using wind screens.
- In the assessment of LFN from any source, including those related to mining activities, it is recommended to measure both near the source and in the far field to understand the reception further away from the source. Acoustic propagation is strongly influenced by temperature and wind conditions in the lower atmosphere as well as the subsurface and are to be considered in the interpretation of LFN measurements.
- It is recommended to further investigate what role low-cost sensors can play in routine LFN measurements.
- In LFN studies (spectral) data samples should be stored and preferably made available, without any processing filtering done during recording. This will allow re-analysis of existing datasets and refinement of workflows.
- Typically, sound pressure levels are reported as averaged quantities including statistical measures of variance. It should be investigated what integration times would be applicable for LFN sources of interest.
- Apply community standards in the reporting of data, including error-bars and meta-data on the response of the measurement system.
- Be aware of special cases, such as modulation, harmonics or Tartini tones, which are not detected by the usual dB(C) measurements or octave band analysis. Additional measurement techniques, such as wavelet analysis, FFT analysis, Cepstrum analysis or order tracking may be necessary.
- Initiatives by citizens with own equipment should be encouraged with knowledge / guidelines / education and support of local organizations. It is important that measurements should be conform the standards as described under 1.

5.3.2 Chapter 3: Sources of LFN

- The available information on LFN from mining facilities is scattered and fragmented. Nevertheless, several cases of LFN have been thoroughly investigated and solved. Collecting the essential information of a dozen cases of LFN problems in the mining industry will be helpful to increase knowledge and solve future problems. A holistic approach is necessary, in which the complaints of the residents, the assessment method and reduction measures are integrated.
- Regarding underground pipelines no clear evidence was found in literature that these may lead to annoyances. However, the number of complaints appear to be on the rise worldwide. A dedicated measurement campaign would be valuable to bridge the seemingly discrepancies between theory, practice, and complaints.
- LFN research and requirements should preferably be integrated as early as possible in the design phase of new facilities or equipment. This may increase the options and reduce the costs, compared to solving issues afterwards. In the commissioning phase of, acceptance tests should be done, which include noise measurements, as well as dedicated LFN measurements.
- In the process of changing burner settings of furnaces and boilers, it is important to monitor sound and vibrations.
- Continuous sound and vibration measurements should be integrated in the Distributed Control Systems (DCS) of mining facilities. This will help to address and focus changing complaints in the environment.
- Develop a catalogue with proven and best practice LFN measures for the most common LFN sources

5.3.3 Chapter 4: Perception, health effects and societal responses

- More research on both exposure and health outcomes could eventually allow for exposure-response curves to be derived.
- When addressing the link between exposure and responses such as annoyance, it is important that the exposure is measured correctly. Most of the currently known studies use energetic measures and broad band sound energy level such as in dB(A) or dB(C). Frequency information is mostly restricted to octave band analysis.
- It is recommended to take several co-determinants into account in future LFN research.
- The situation should dictate the research methods: research is possible for a single individual (taking for instance individual hearing thresholds into account) or for a community. Be aware that the choice for a certain method allows insight in some factors, but not in all possible factors.
- More focused research is also needed that considers reports of LFN and actual measurements of LFN from potential LFN sources in the vicinity of those complaints. As the contribution of these sources to the LFN field is not well understood, it is difficult to assess individual reports. It should always be verified if the reported LFN is part of the audio or the sub-audio band (Section 4.2.1.2). If the possibility of an acoustic cause can be excluded, further investigations on co-determinants, psycho-acoustical effects, or neurological phenomena are recommended.
- It is recommended to investigate the role of psychoacoustic effects such as Tartini (combination) tones, beating/modulation, binaural effects, and tonal effects.
- To develop a better understanding of LFN with the public, it may be helpful to develop an online platform as a tool to better inform people about differences in frequency and various analysis methods. This could also help to let people distinguish different spectral bands, i.e., those below and above 200 Hz.
- Develop regional expertise on the assessment of LFN complaints. This way, research procedures can be standardized such that common mistakes can be prevented and typical sources, such as 50 Hz electricity related hums, can be identified more efficiently.
- Besides the sharing of expertise, facilitate the sharing of equipment so expensive measurement devices are available to communities, for example within a region.

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7 Appendix

For each work package, experts from a representative selection of organizations (academia, research institutes, engineering firms, instrument manufacturers, suppliers of measuring instruments and machinery for mining activities) have been interviewed to get a broad perspective. The interviews have been used to help direct the literature review.

The following sections provide information on the names of interviewees, their organizations, and the expertise for which they have been contacted.

7.1 Interviewees WP1

	Name	**Organization**	**Expertise**
1	Robert Baars	Tata Steel	Equipment and process industry; LFN from pipelines
2	Pieter van Beek	TNO	Rotating equipment LFN in oil/gas industry
3	Maarten van de Berg	VB Geo Projects	Geothermal systems
4	Eric Dorenbos	NAM	Oil/gas industry
5	Koos Huijsmans	Aardyn	Geothermal systems
6	Dirk Hiemstra	Gasunie	Natural gas storage and infrastructure
7	Helen Roessink, Abel Jan Smit	Nedmag	Salt mining

7.2 WP2 - List of interviewees

	Name	Organization	Expertise
1	Frits van den Berg*	University of Groningen (retired) Municipal Health Service (GGD) (retired)	Researcher of LFN complaints Adviser on noise perception
2	Hans-Elias de Bree	Co-founder Microflown Technologies B.V.	LFN measurement equipment
3	Bernard Dost	Royal Netherlands Meteorological Institute (KNMI)	Monitoring of induced seismicity in the Netherlands
4	Läslo Evers	Royal Netherlands Meteorological Institute (KNMI) Delft University of Technology	Infrasound Seismo-acoustics Propagation modeling
5	Julius Fricke	DGMR raadgevende ingenieurs BV	LFN monitoring consultancy
	Hans J.A. van Leeuwen	Noise, vibration & air consultant (NVAC) Past: DGMR raadgevende ingenieurs BV	LFN monitoring consultancy
6	Maarten Hornikx	Technical University Eindhoven (TU/e)	Building acoustics Propagation modeling
7	Jan van Muijlwijk*	Municipality of Veendam, Groningen (retired) Omgevingsdienst Groningen (retired)	LFN monitoring Perception
8	Anneke Teheux – Dalstra Bob Gaasbeek	ENMO Sound & Vibration Technology, Belgium/Ne	LFN measurement equipment LFN consultancy
9	Roger Waxler	National Center for Physical Acoustics (NPCA) at the University of Mississippi	LFN measurement equipment Propagation modeling

* Also consulted on the topic of perception (WP3)

7.3 WP3 - List of interviewees

	Name	**Organization**	**Expertise**
1	Frits van den Berg*	University of Groningen (retired) Municipal Health Service (GGD) (retired)	Researcher of LFN complaints Adviser on noise perception
2		State Supervision of Mines (SSM / SodM)	LFN noise complaints specific to mining
3	Henk Janssen	Omgevingsdienst Noordzeekanaalgebied	Public Health Authority LFN noise complaints
4	Jan van Muijlwijk*	Municipality of Veendam, Groningen (retired) Omgevingsdienst Groningen (retired)	LFN monitoring Perception
5	Erik Roelofsen	Nederlandse Stichting Geluidshinder (NSG)	Perception LFN complaints

* Also consulted on the topic of monitoring (WP2)