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A fast spray-proof anemometer

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A FAST SPRAY-PROOF ANEMOMETER

1. Introduction.

During the first stage of the development of an air-sea interaction programme for the Royal Netherlands Meteorological Institute it was realized that all commercially available wind sensors have their shortcomings when used in the marine atmosphere in the proximity of the waves. It was decided then to take in hand the construction of a fast-responding three-dimensional anemometer of fairly small dimensions that would be resistant to spray, salt-accretion and rain. This research note is a survey of the results obtained till now.

2. Working principle.

The anemometer is based on the following principle (fig. 1). Compressed air flows in through the vertical leg of a T-junction and flows out to the atmosphere through the two horizontal arms of the junction, after having passed a constriction. At symmetrical points the static pressure of the air inside the arms is measured. If a wind blows, the pressure in the windward arm is higher than the one in the leeward arm; the pressure difference is a measure for the wind velocity.

In a variation on the principle the measurement of the pressure difference is substituted by a velocity difference measurement: the velocity of the air in the two arms is measured with hot wires, the velocity difference is a measure for the (external) wind velocity.

To make the anemometer three-dimensional, three mutually orthogonal (or, at least not coplanar) pairs of outflow tubes are to be combined in a single instrument. From the three signals the wind vector components can be derived if the orientation and the angular dependence of the response of the instrument are known.

3. Functioning.

3.1. General.

In general the reaction of the internal flow of the instrument on an outside wind fluctuation can be considered as instantaneous (see 5). Then an equilibrium exists between the total pressure outside the anemometer and the total pressure in the outflow tubes. In this case two equations can be written down for the one-dimensional version:

$$p_o + \lambda_w \cdot \tfrac{1}{2} \rho u^2 = p_w + \tfrac{1}{2} \rho s_w^2 \qquad (1.a)$$

$$p_o - \lambda_l \cdot \tfrac{1}{2} \rho u^2 = p_l + \tfrac{1}{2} \rho s_l^2 \qquad (1.b)$$

Equation (1.a) is for the windward, (1.b) for the leeward arm. p_o is the ambient static pressure, u is the external velocity component along the axis of the instrument, p_w the static pressure measured in the windward arm and s_w the internal velocity in that arm; p_l and s_l are the static pressure and the velocity in the leeward arm. λ_w and λ_l denote the modification of the external dynamic pressure at the windward and leeward side due to interaction with the anemometer. The sign of the term with λ_l is chosen negative, as, apart from modifications contained in λ_l, the dynamic pressure would lower the pressure on the opening of the outflow tube at the leeward side. In equations (1) the gradient in the static pressure over the dimensions of the anemometer has been neglected ($p_{o,w} = p_{o,l}$), as well as friction effects in the outflow tubes.

The relation between the constant inlet pressure P and the pressure and velocity in the arms can be approximated as

$$P - p_w = C \rho s_w^2 \qquad (2.a)$$

$$P - p_l = C \rho s_l^2 \qquad (2.b)$$

in which C is a dimensionless coefficient, depending mainly on the dimensions of the anemometer. C is always larger than 0.5 (the value for frictionless flow) and increases with the internal flow resistance (smaller openings, longer tubes etc.) as may be expected from (2).

Since the adequate functioning of the instrument requires that s_w is positive, the maximum wind velocity which can be measured, u_{max}, is fixed by the relation

$$\lambda_w \cdot \tfrac{1}{2} \rho u_{max}^2 = P - p_o \tag{3}$$

which follows from (1.a) and (2.a) by putting $s_w = 0$. In this case stagnation occurs in the windward arm and $p_w = P$, as follows from (2.a).

3.2. Pressure mode.

Eliminating s_w and s_l from (1) and (2) and subtracting the resulting equations from each other, an equation for the relation between u and $p_w - p_l$ may be derived:

$$\lambda \cdot \tfrac{1}{2} \rho u^2 = (1 - \frac{1}{2C}) (p_w - p_l) \tag{4}$$

with $\lambda = \lambda_w + \lambda_l$.

From (4) it is clear that for a given u the pressure difference is maximized by making C as large as possible. C is limited by the fact that the flow through the constriction has to be subsonic because Eqs.(2) are no longer valid with a sonic velocity in the constriction: the sensitivity of the apparatus then becomes lower.
The disadvantages of the system are clear from (4). The basically quadratic velocity response is a limiting factor for the range of the instrument; especially the measurement of low velocities is difficult, due to the low pressure differences. The response is complicated once more by the factor λ , which depends on the shape of the apparatus and on the internal and external velocities.

In the configuration we mostly used for the pressure version of the anemometer, the constriction is a cylindrical opening with a diameter of 0.4 mm and a length of 1 mm. A value of $P - p_o$ = 80 mbar results in $s_w = s_1 \simeq 2$ m/s at $u = 0$. $p_w - p_1$ is 5 to 10 μbar at $u = 1$ m/s and about 3 mbar at $u = 18$ m/s. Fig. 2 shows, that the experimentally obtained relation between wind speed and signal is indeed approximately quadratic.

3.3. Velocity mode.

The relation between u and $s_w - s_1$ can be found from (1) and (2) by eliminating p_w and p_1 and subtraction of the resulting equations, leading to

$$\lambda \tfrac{1}{2} \rho u^2 = (C - \tfrac{1}{2})\ \rho\ (s_1^2 - s_w^2) = 2\ (C - \tfrac{1}{2})\ \rho\ \bar{s}\ \ (s_1 - s_w) \qquad (5)$$

with $\bar{s} = 0.5\ (s_1 + s_w)$.
For low values of u, $\bar{s}$ can be approximated by

$$\bar{s} = \left\{ (P - p_o) / (C - \tfrac{1}{2})\ \rho \right\}^{\frac{1}{2}},$$

as follows from (1) and (2).
Then (5) becomes approximately

$$\lambda . \tfrac{1}{2} \rho u^2 \simeq 2 \left\{ (C - \tfrac{1}{2})\ \rho\ (P - p_o) \right\}^{\frac{1}{2}} . (s_1 - s_w)$$

The signal -in this case the velocity difference $s_1 - s_w$, measured with hot wires- is maximized by making both C and $P - p_o$ as low as possible. The supply pressure excess $P - p_o$ should be chosen much lower than in the pressure mode described above. It has to be higher, however, than the value determining the desired measuring range of the instrument, according to (3). If $P - p_o$ is fixed, s_1 and s_w will increase as C is lowered. These higher outflow velocities cause a more than proportional increase in the turbulence level in the arms, thus limiting the lowest detectable velocity difference. In this way there exists also a lower limit for C. The most sensitive arrangement we used gave a lowest detectable signal of 6 μV at an external velocity u less than 20 cm/s; $P - p_o$ was about 0,5 mbar and stagnation occurred at about 9 m/s. An arrangement with a slightly higher C gave a lowest detectable signal of 15 μV at a velocity of 60 cm/s and no stagnation up till 18 m/s, the maximum velocity in our windtunnel; the supply pressure then was a few millibars.
The numbers given have only an illustrative meaning. They were obtained with the arrangement depicted schematically in fig. 4 and

depend on the overheating ratio of the hot wires, their stability, the supply pressure and the degree to which turbulence in the outflow tubes can be suppressed. The way in which we suppressed the turbulence is indicated in fig. 3. The air is passed through a fine mesh grid (hole diameter 0.06 mm, open area 22.5%) which acts as a constriction and as a turbulence sieve, and after that through rectifier tubes (inner diameter 0.9 mm). Then a contraction follows behind which the hot wire is mounted.

4. Angular dependence.

Our experiments on the angular dependence of the anemometer have concentrated on a spherically shaped instrument, as this is the most simple model for a three-dimensional version, which is our final purpose. Up till now we have experimented with a one-dimensional version, embedded in a sphere; a few experiments with a cylindrically shaped envelope showed a very unsatisfactory angular dependence.

The enveloping sphere we used had a diameter of 10 cm with roughness elements with a height of 0.2 cm. The most promising system had conical outflow openings with an apex of 150° and small disks in front of the outflow openings. This system gave an angular dependence which varied between 0.35 and 1.53 percent of the maximum signal (i.e. the signal when the instrument axis is aligned with the wind vector) per degree. The low value was found near an angle of 0° between instrument axis and wind vector, the high value in the neighbourhood of 50°. The angular dependence was fairly linear between 30 and 80°. These values showed no significant variation with changes in velocity during a few preliminary experiments.

5. Frequency response.

The dimensions of the apparatus are the limiting factor for the high frequency response. Taking 5 cm as the minimum length of the anemometer and the maximum windspeed as 20 m/s, the maximum frequency that can be measured with some sense is 400 Hz. As mentioned earlier the reactions of the internal flow system are very fast; in fact the velocity of sound is the limiting factor here (this being the maximum velocity with which a small pressure disturbance can be transported). This means that the maximum detectable frequency, as regards the internal flow system, would be of the order of 10 kHz, and its reactions can be taken as instantaneous.

The pressure or velocity detecting system has its own frequency dependency. In the pressure detecting system a differential manometer has to be connected to the anemometer by some length of tubing. This tubing will bring down the maximum frequency quite fast (Iberall, 1950), while the frequency response of the differential manometer itself may also be a limiting factor.

When hot wires are used it is impossible, when one wishes to use constant temperature systems, to use the two hot wires in a single bridge, as the hot wires are acting with a 180° phase difference and the two linked systems would try to compensate each other. This means that two fully separated systems have to be used and that their outputs are to be compared, allowing for differences between the hot wires and the systems themselves. It does not seem feasible at this stage to try to develop such a combination.

We have used the slower constant current system and used the two hot wires in neighbouring arms of a simple bridge arrangement, as indicated in fig. 4. This limits the frequency response to about 100 Hz, which is sufficient for many applications.

6. Air consumption.

The measured air consumption of the pressure version of the apparatus, which has a constriction of 0.4 mm diameter, was 102 litres per hour, at a supply pressure of 80 mbar. The air consumption of the velocity version was the same at a supply pressure of ~ 2 mbar.
Instead of compressed air other gases can be used; CO_2 for instance would have advantages with respect to storage and transportation of the gas, when the anemometer is used in places where not enough power for a compressor system is available.

7. Final remarks.

The advantages of the instrument are clear: it is small, fairly fast, rugged, three-dimensional, has no moving parts, and is self-cleaning. It can work under conditions where other instruments get clogged or deteriorate rapidly.
Some problems still have to be solved. Although there are commercially available pressure sensors that are sufficiently fast and sensitive, these

have to be mounted at some distance of the anemometer to prevent an extra distortion of the windfield. This asks for tubing, thus lowering the frequency response. Another problem is the angular dependence, which is not fully as desired. We nevertheless felt justified in presenting the principle and some details as it is clear at this stage that the instrument shows a number of very desirable properties.

8. Acknowledgement.

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References.

Iberall, 1950	Iberall, A.S., J.Res.Nat.B.of Stand. 45 (1950), 85.

Figure captions.

fig. 1. Principle of the anemometer.
1. Inflow tube. 2. Constrictions. 3. Pressure measuring points.
4. Plates to break the jets, issuing from the constrictions.

fig. 2. Pressure difference-velocity relationship. Inlet pressure 0.1 atm.

fig. 3. Anemometer type for use with hot wires.
1. Grid. 2. Rectifier tubelets. 3. Hot wire.

fig. 4. Bridge-circuit for use with hot wires. The resistance R_T can be connected parallel to one of the hot wires to compensate to some extent the differences between the hot wires.

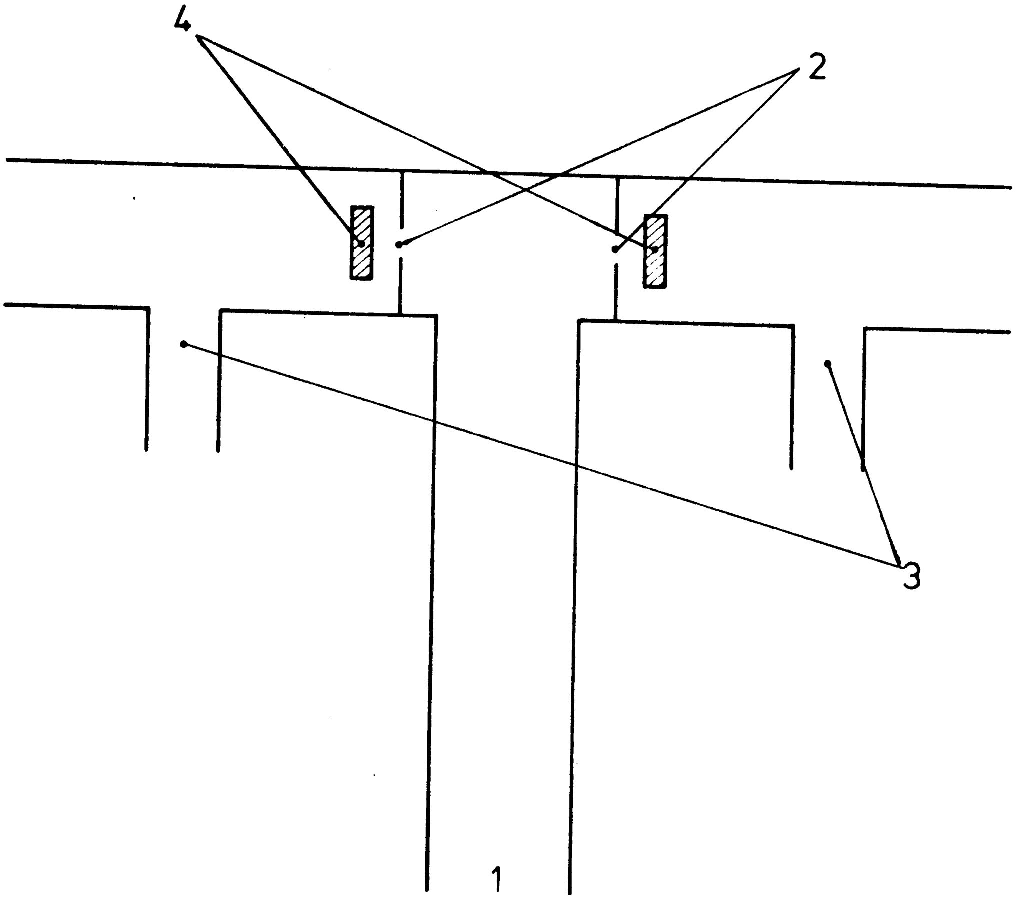

fig. 1

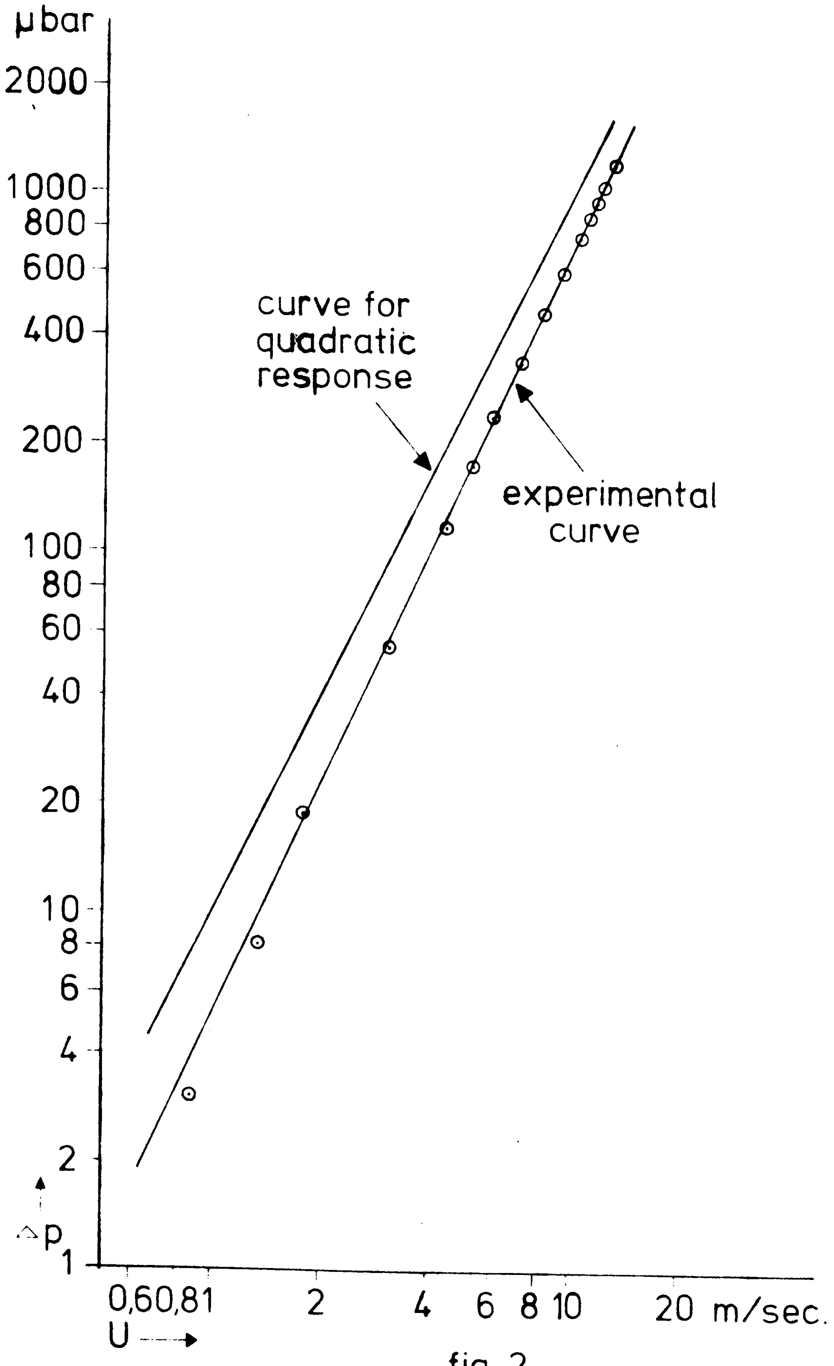
µbar
2000
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
Δp
curve for quadratic response
experimental curve
0,6
0,8
1
2
4
6
8
10
20 m/sec.
U

fig. 2

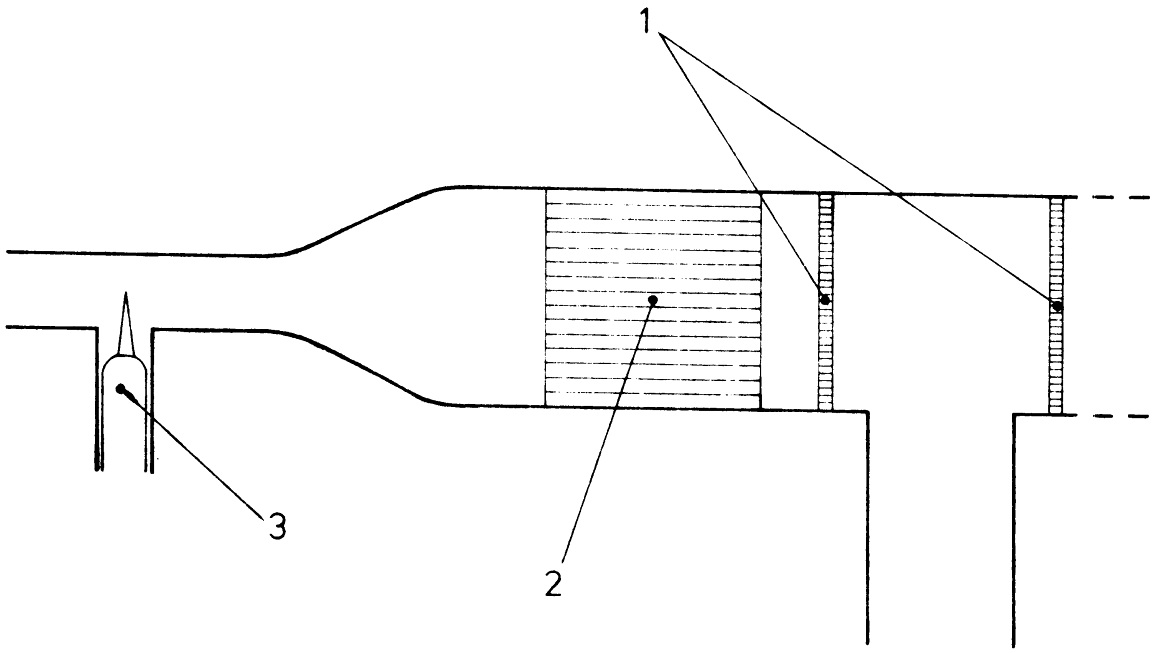

fig. 3

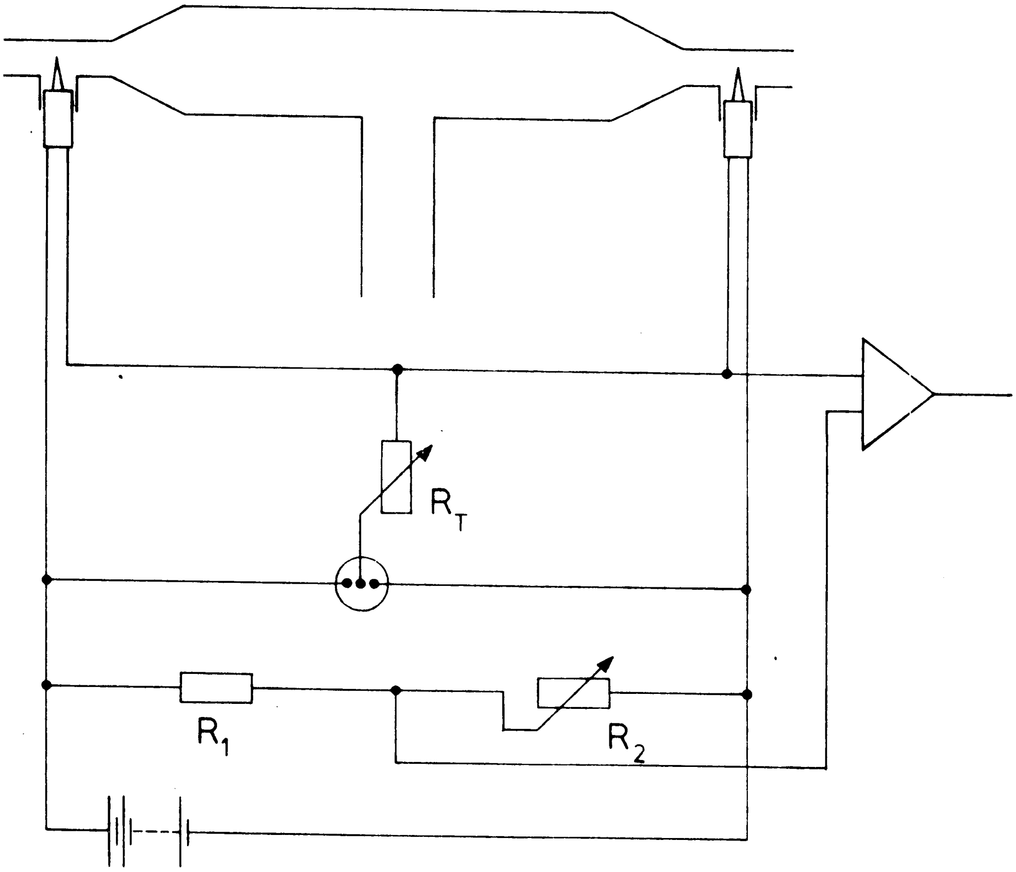

fig. 4