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Observational Study of Turbulent Structure of High Winds Part 1

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Abstract

The requirements on knowledge of wind environments on structures in high winds are reviewed. They are summarized in information on short period fluctuations and spatial distribution of wind gusts. To fulfill these requirements the traditional anemometers are not satisfactory in their response characteristics to use in observational studies. Thus the new type pressure tube anemometer was developed and taken as the first step in the study of wind structures. The details of the new anemometer are explained in this paper.

1. Introduction

Recent developments in structural engineering and social needs have made it possible to construct large structures such as tall buildings, long bridges, tall towers or stacks and large radio antenae. The problem of wind loads acting on these giant and flexible structures is one of growing concern in civil engineering. In fact, wind loads are at present the primary consideration in designing the long suspension bridge connecting the two main islands of Japan. Since the existing design code is not enough to be applied to the design of such large structures as long bridges or skyscrapers, it is necessary that our knowledge of wind environments be increased.

The present authors and their collaborators are undertaking extensive studies on the nature of wind environments and the responses of structures to the wind loads from observational and theoretical points of view. This is the first report concerning the observational study of wind environments in stormy conditions. In this report, the new presssure tube type anemometer specially designed for this study, is explained.

2. Review of the problems

The fundamental natural periods of the structures range mostly a few to a few tenths of seconds. Thus short period fluctuations of wind environments at least down to this range should be determined, which is pointed out in the recent studies on structural theory and structural failures in the past. Deacon[1] has used specially designed Sheappard type cup anemometers down to averaging time of 2 sec in the design problem of radio masts, while Sherlock[2] has used specially designed pressure plate anemometers and analyzed fluctuations down to 1/4 sec. However shorter frequency ranges have never been studied. Recently Davenport[3] has studied this problem from the theoretical point of view and reduced the problem of effects of short period wind changes to a statistical problem, using power spectral density considerations, but observational knowledge is still lacking in cases of high wind.

Another problem in the structure of wind environments is their spatial structure or the relation between point-observed wind fluctuations and the total wind pressure on the structure, which is assumed to be the integrated effect of the point values over the whole surface area. The short period changes are naturally short in their wave length and, therefore, in their lateral scale. The expected wave length of fluctuations of 10 cps in frequency in mean wind of 20 m/sec is only 2 m, and such fluctuations cannot be expected to affect the whole structure of several tens meters at the same time. Thus it is anticipated that the wind load, estimated simply from the results of point observation would be overestimated. One of the present authors has tried to study this problem from observations (Ishizaki[4]), but the scale of the space studied was so small that only general deductions could be made. From the theoretical point of view, the present authors[5] have tried to estimate the lateral scale of gusts, using a simple hypothesis on the relation between the lateral and longitudinal scale of turbulence. And recently Davenport[6] studied this problem from the statistical point of view also, by means of cross spectral considerations. But the observational verifications of these ideas are entirely lacking.

The essential requirements for further information on wind environments can be summarized as follows; 1) the character of high frequency wind fluctuations up to about 10 cps, and 2) the spatial distribution or structure of such short gusts. For these purposes we shoud use a large number of high frequency resolving anemometers distributed in the aerial space of about the same dimension as the structure. But anemometers used in ordinary weather observations cannot resolve such high frequency changes, so it was necessary to make the new anemometer first as described in the following pages.

3. The limitations of the traditional anemometers

The cup or propeller type anemometer has been used in weather observations throughout the world. But ordinary anemometers are not so quick in response to high frequency wind fluctuations. The cutoff frequencies of the traditional anemometers in Japan, which were calculated by Miyata[7], based on the studies by Sanuki[8], are shown in Table 1. As is clear from this table, their frequency responses are not high enough for the present purpose. To make the frequency

TABLE 1.

Frequency limit of 90% response in amplitude of traditional anemometers (in cps).

	10m/sec	20m/sec	40m/sec
3-cup (FC-1)	0.10	0.21	0.40
4-cup (FC-2)	0.08	0.16	0.31
Propeller (FF-1)	0.22	0.46	0.91
Sheppard Type	0.36	0.75	1.48
Dines		0.08	

response character of anemometers of this kind satisfactory, several studies have been made. But the essential limitations in strength and weight prevent improvements and the Sheppard type which was used by Deacon[1] may be the limit; its response character is shown in Table 1.

Another typical traditional method of anemometry is heat flow devices, such as hot wire anemometers. By this instrument we can resolve very high frequency wind changes in the laboratory, but to make use of it in the field and in high winds is extremely difficult because of its delicacy in many points.

Dines anemometer has been used to observe gust wind speed and is thought to have had good responses to wind fluctuations. But, in fact, its frequency response is not so good, as is pointed out by Yajima[9], and it was replaced by the propeller type anemometer, which has a better response character. The typical characteristics determined by Yajima is shown in Table 1. But, as is shown by Sanuki[8], the main cause for the drop in response is the long tubing from the sensor to the transducer. Therefore, if we can reduce the length of pipe and also develop a high response pressure transducer, it is possible to get a fast response anemometer in pressure tube type sensor, which is adopted in the present study as shown later.

The drag plate or sphere type anemometers have been used most commonly in the study of storm gusts (Sherlock[2], Ishizaki[4], Reed et al[10]). It may be sufficient for the study of the resultant wind forces on the structure members but is not appropriate for wind studies. It measures the actual wind forces on the sensor of certain shape and dimension, and they are affected by the Reynolds numbers or angle of wind incidence, and these indefinite characters prevent our evaluation of winds.

The sonic anemometer is one of the most promising instruments in this field of study, because it can measure wind velocity component in any desired direction accurately, and high frequency wind flutuations easily (Mitsuta[11]). This will certainly become the principal instrument in future study, but at present it is rather expensive and unreliable in field work in storms.

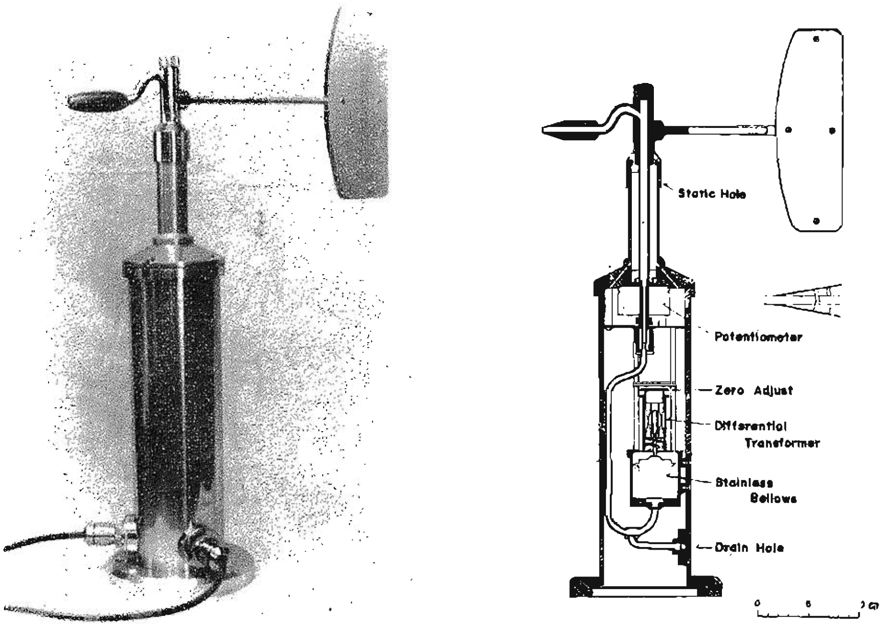
4. New type pressure tube anemometer

The requirements for an anemometer in the present study are to resolve high frequency wind fluctuations up to about 10 cps and to have high reliability even in stormy conditions. We could not find a suitable anemometer meeting these requirements among traditional ones mentioned above. It is the primary object, therefore, of the present study to develop a new anemometer.

There are significant advantages in measuring velocity pressure directly for the study of wind effects. As wind direction changes widely and rapidly, the instrument used in the wind tunnel test, such as the pitot-static tube, is not suitable as the sensor in this case, but the Dines anemometer type is. To direct the pressure tube to wind direction by wind vane has some defects in its response character, and it is not so easy to increase the response. But as we could not find any alternatives, we succeeded with this method, using a specially designed wind vane.

The new type anemometer consists of the pressure tube which rotates with the wind vane, the pressure transducer which is built in the sensor, the potentiometer as wind direction transducer and the electric component with output devices. The total wind pressure is detected by the pressure tube, which is connected with the bellows of stainless steel by a short pipe of about 30 cm in length and 6 mm in inner diameter. The static holes are open under the sleeve of the wind vane and the pressure in the sensor is equal to the static pressure. Therefore the pressure difference between inside and outside the bellows is equal to the velocity pressure. The displacement of the bellows, which is proportional to the velocity pressure, is converted into electrical signals by the differential transformer and then into the voltage analogue output by the displacement meter. The wind direction transducer is a potentiometer built in the sensor, whose axis rotates with wind vane.

The new anemometer is shown in Fig. 1 and Fig. 2. The sensor is shown in Fig. 1 and the electric component, which is capable of six channels detection, is shown in Fig. 2. The electric component is a commercially available multichannel displacement meter (Shinko MI-6W-11). The total height of the sensor which is shown in Fig. 1, is about 60 cm and the dimension of the wind vane is about 6.5×20 cm. The drain hole at the bottom of the sensor is to drain out rain water that leaks into the pipe, but it was not necessary to open it during the years of obsevation. The diameter of the bellows is about 4 cm. The zero adjusting screw is to move the differential transformer adjusting the zero point of the output. The differential transformer (Shinko DS-36S-M) is excited by stabilized A. C. current of 1.2 kc. As the exciting frequency is high enough, frequency response of the system is satisfactory.



(a) (b)

Fig. 1. Outside view (a) and details (b) of the new anemometer.

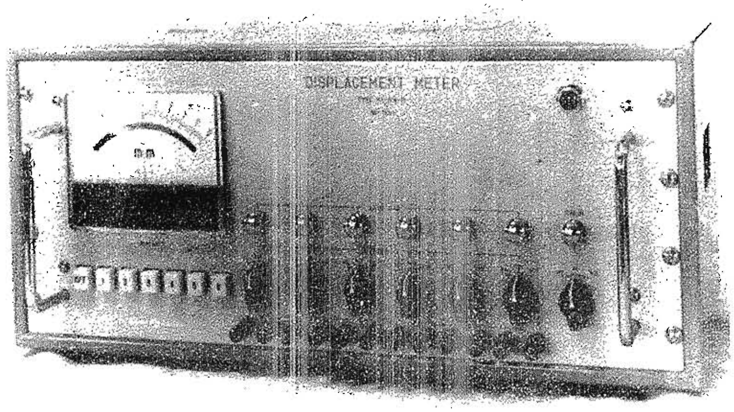


Fig. 2. Electric component of the new anemometer (6 channel type).

The displacement of the bellows is shown as follows

$$X=k\ (p_1-p_0) \qquad \cdots\cdots(1)$$

where p_1 is pressure in the bellows, p_0 static pressure, X displacement and k modulus of elasticity of the bellows. The average value of k is 0.29×10^{-2}mm/mmAq. The electrical output is proportional to this displacement and is 1.45×10^{-3}V/mmAq for output impedance of 500 ohms. The linear pressure-displacement relation does not hold good when wind speed is less than 5 m/sec or so, but this range is out of our interest in this study.

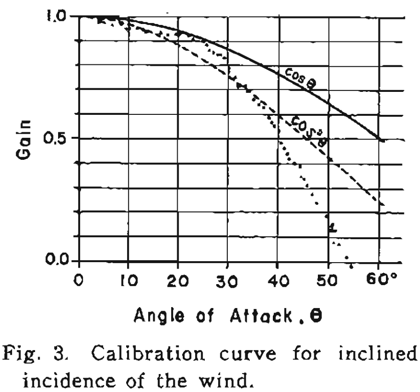


Fig. 3. Calibration curve for inclined incidence of the wind.

The Pitot coefficient of the pressure tube was tested in the wind tunnel of the Disaster Prevention Research Institute. The average value is 0.87, which means the velocity pressure measured by this sensor, being reduced by the factor of 0.87. This comes from the shape of the sensor. The decreasing of the output when wind comes from a different direction than from the axis of the pressure tube was also checked in the wind tunnel. The results are shown in Fig. 3. As is seen, the relation between the relative output and the angle of attack is neither cosine nor cosine squared relation, especially in the case of the large angle of attack.

5. Dynamic response of the new anemometer

The transducing system of the new anemometer can be summarized in the diagram shown in Fig. 4. The equation of motion of the core of the differential transformer which is fixed to the bellows is given as follows:

$$m\ddot{X}=kX+A(p_1-p_0) \qquad \cdots\cdots\cdots(2)$$

where X is displacement of the core as in eq. (1), m mass of the system including the core, A effective area of the bellows and p_1 and p_0 the same as in eq. (1). The equation of continuity of the air in the sensor is given as follows, disregarding compressibility of air,

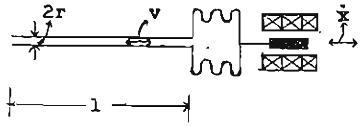


Fig. 4. Schematic diagram of the sensor.

$$sv=A\dot{X} \qquad \cdots\cdots\cdots\cdots\cdots\cdots(3)$$

where s is the cross sectional area of the pipe and v mean air velocity in the pipe. As displacement of the bellows is less than 1 mm in most cases, the air flow in the pipe is so small that we assume it to be Hagen-Poiseuille flow. Then air velocity in the pipe is approximated by

$$v=\frac{s}{8\pi\mu l}(p-p_1) \qquad \cdots\cdots\cdots\cdots\cdots\cdots(4)$$

where μ is viscocity of air, l length of the pipe and p total pressure at the opening of the pipe. Then the equation of motion becomes

$$m\ddot{X}+c\dot{X}-kX=Aq \qquad \cdots\cdots\cdots\cdots\cdots\cdots(5)$$

where $c=8\pi\mu lA^2/s^2$ and q velocity pressure $(=p-p_0)$. Eq. 5 shows that the response character of the new anemometer can be analyzed as the second order response system, and its character is expressed by two parameters, e. g. free period and damping ratio. The solution of this equation has been studied. When the wind fluctuation is sinusoidal and wind speed is written as

$$q=[1+g\sin(2\pi t/T)]q_0 \qquad \cdots\cdots\cdots\cdots\cdots\cdots(6)$$

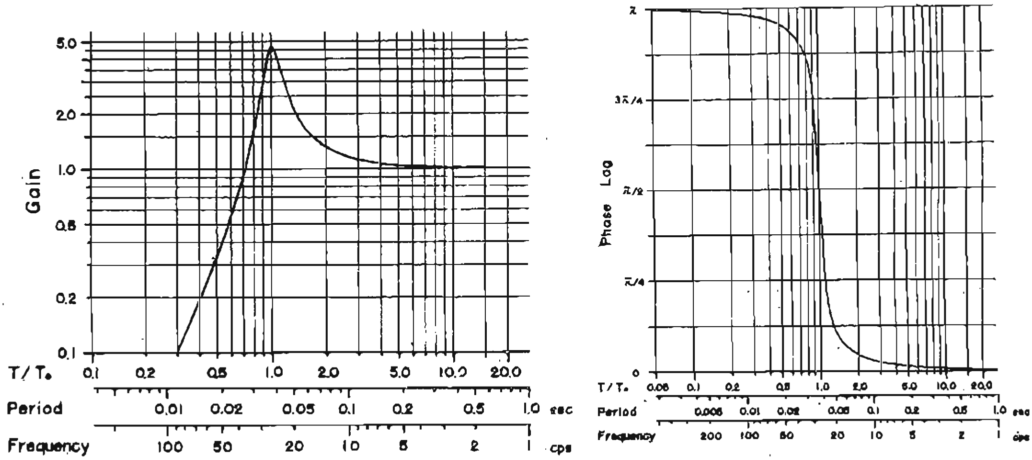
where g is relative amplitude, T period of wind fluctuation and q mean velocity pressure, the movement of the core or output in stationary condition can be shown as follows

$$Q=[1+Mg\sin(2\pi t/T-\delta)]q_0 \qquad \cdots\cdots\cdots\cdots\cdots\cdots(7)$$

where M is amplitude gain and δ phase lag.

The parameters of the new anemometer were tested experimentally from the transient response character to the stepwise pressure change. The free period T is 0.038 sec and logarithmic damping ratio is 0.33. Variations of gain M and phase lag, with the period of wind fluctuation T, are calculated and shown in Fig. 5. Because of small damping ratio a significant peak in amplitude gain is seen at the point $T=T_0$. But this peak is far from the ranges that we want to analyze and wind fluctuations in such a short period might be small. So the frequency response of this anemometer is almost satisfactory, though we must take into account the exaggeration of fluctuation of higher frequency on the trace. The phase lag is less than 5 degrees for the changes is which the frequency is lower than 10 cps and it can be disregarded in practice.

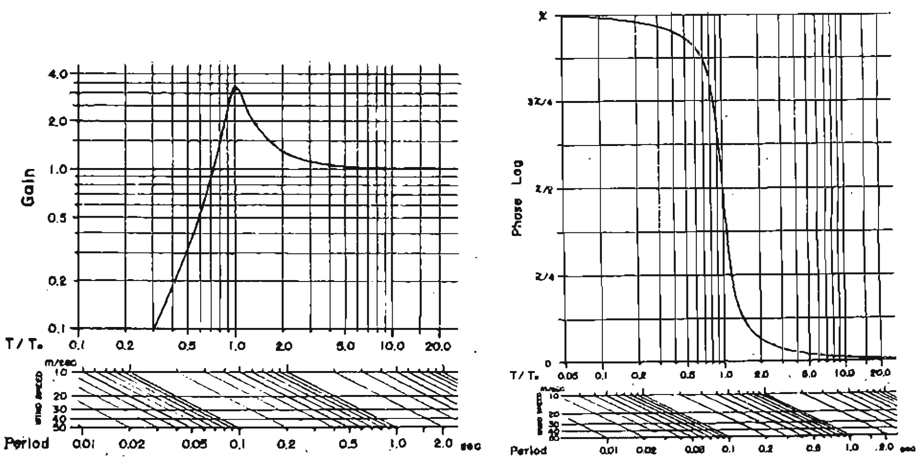
The response of wind vane motion, when the wind changes its direction, has been studied by Sanuki[8] and it is shown that the response character is also



(a) Amplitude gain (b) Phase lag

Fig. 5. Frequency response of the new anemometer.

described as the second order system. The parameters of the new anemometer as wind vane were tested in the wind tunnel by the method proposed by Sanuki. As a result the following values were obtained; free period being 4.7/V sec, where V is wind speed written in m/sec and logarithmic damping ratio being 0.49. These values are much better than these of the traditional wind vane. The frequency response diagram, calculated from these values, is shown in Fig. 6. The peak value of the amplitude gain is 3.3 and the free period is 0.47 sec in wind speed 10 m/sec and 0.094 sec in 50 m/sec. The peak value of the amplitude gain is in the range which we want to know and this may cause



(a) Amplitude gain (b) Phase lag

Fig. 6. Frequency response of the new anemometer as wind vane.

some effects also in anemometry. However wind direction changes in such high frequency ranges as 10 cps can be also regarded as very small in amplitude. Therefore the effect on anemometry may be comparatively small and there is no need for correction.

An example of the traces of the new type anemometer, as obtained in storm observation, is shown in Fig. 7 where four anemometers are placed with some horizontal spacings of about 6 to 20 meters at the same height of 11 meters. The time marks at the bottom of the record are at one second intervals.

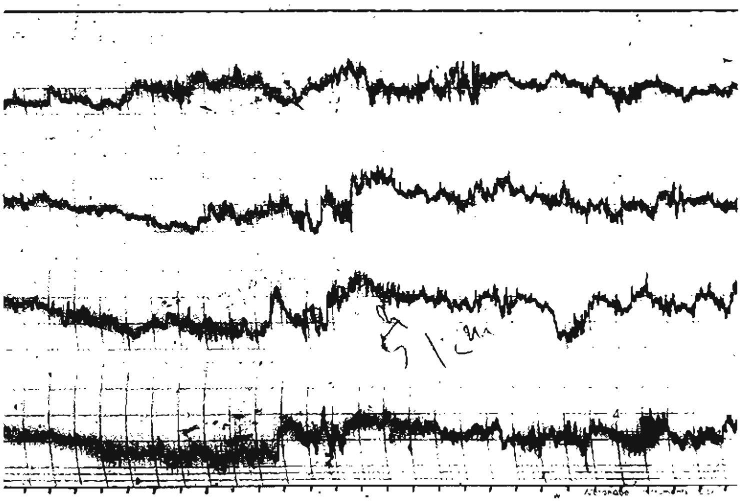


Fig. 7. An example of the traces of the new anemometer.

6. Conclusion

The new pressure tube anemometer has been made, as the first step in the study of wind environment. The response character of new anemometer has been studied and the results are almost entirely satisfactory. The results of storm observation by the use of this anemometer will be reported in the following parts of this paper.

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