On the Vibration of a Cylindrical Tower Structure Induced by Strong Winds

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Abstract

The lateral vibration of a cylindrical tower structure induced by strong wind is presented. We observed the amplitudes of displacement at the top of Kyoto Tower, when Typhoon No. 24 passed over the Kinki District in 1965. The typhoon was attended with a maximum peak gust of 51m/sec at the top, and we shall discuss some problems below the mean wind speed of 35.5m/sec. Before the relationship between the amplitudes and the wind speed is clarified, the duration time of the fluctuating wind velocity will be dealt with to fit the characteristics of the structure. In this range of wind speed the maximum amplitude arises at 28m/sec.

1. Introduction

Kyoto Tower in the central part of Kyoto City was completed 1964. It is a cylindrical structure of steel with a circular section, and was erected on top of a building constructed of steel reinforced concrete. The general view of the tower is shown in Fig. 1.

Because we are concerned only with the oscillation of the tower due to strong winds, several vibrometers, anemometers and an oscillograph recorder were installed on the tower. The first measurement was carried out during the period from March 10th to April 30th 1965, and we got our records with a moderate wind speed within 20m/sec. The second was on September 17th, when typhoon No. 24 struck the Kinki District in 1965 and the maximum peak gust of the observed wind was 51m/sec at the top of the tower.

Although many papers on the oscillation of such cylindrical tower structure as high steel stacks have been presented, our knowledge concerning this problem is still not sufficient. In designing a tower structure, it is difficult to estimate the proper lateral forces, amplitudes and critical wind speeds. The facts clarified by previous research[1),2)] are as follows:- in most cases the structure oscillates with a natural frequency, the lateral amplitudes are remarkable and vortex shedding like a Karman vortex street induces alternating lateral forces.

2. Method of Observation

The Tower is 79.11m in height with a circular cylinder section and pierces through the discal observatory. The antenna pole and the "target" (its support) with a rectangular section are attached to its top. Pick-ups for vibrations were set in the circular cylinder part, where simultaneous records of amplitudes and wind speeds were obtained. The direction of the pendulums of moving coil type vibrometers and subsidiary C type vibrometers were from East to West and from

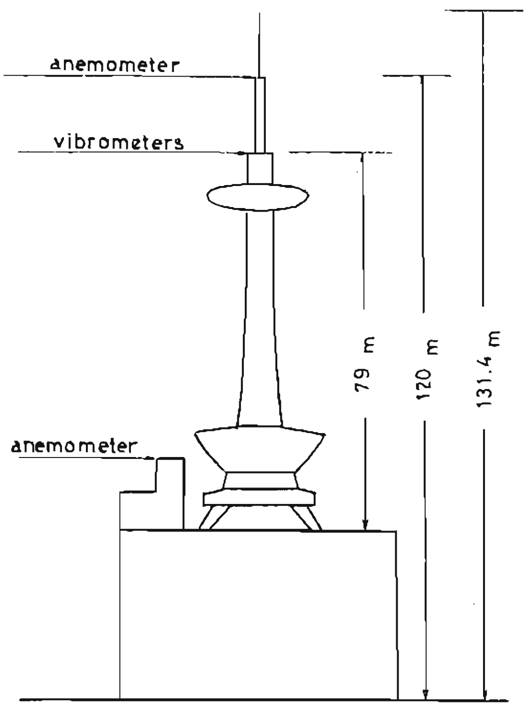

Fig. 1 The posotion of the instruments.

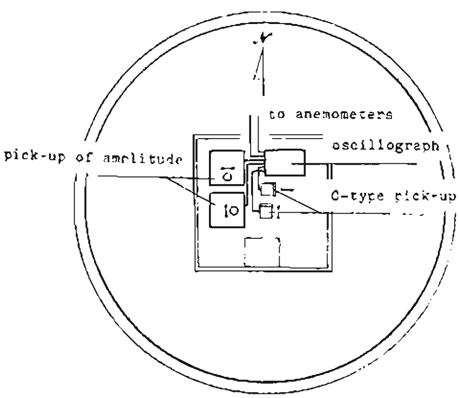

Fig. 2 Arrangement of the instruments.

North to South respectively. Two propeller type anemometers were set at heights of 120 and 42m from the ground respectively. Each output from them was simultaneously recorded on an oscillograph as shown in Fig. 2.

3. Results of Measurement

(1) Movement of the top of tower

It was observed that the tower oscillated generally in a fundamental bending mode, and that its period was about 1.3sec both in the east-west and north-south directions, although it became slightly longer as the amplitudes increased. Oscillations rarely occurred in a vertical plane. The locus of the movement at the top was generally elliptic and changed its axis and the length of the axis step by step. Fig. 3 shows the transition of displacement, when the wind blew almost towards the west with velocity of 18m/sec, averaged over one minute. The numbers in Fig. 3 indicate the rotating times of an elliptic circuit.

It is convenient to divide a transition period into three stages in order that we may consider the mechanism of the oscillation from the configuration of the motion at the top. At the first stage Fig. 3 (a) the amplitude grows abruptly near a point lateral to the wind direction, as if there were resonance of forced vibration. This phenomenon implies that energy is conducted to the system of vibration, and may suggest that an alternating lift force is induced by the movement

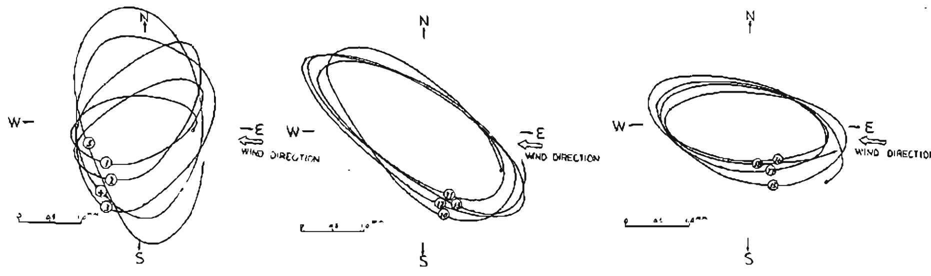

Fig. 3 Movement at the top of the tower.

of the tower. At the second stage Fig. 3 (b), the growth of the amplitude has a certain limit caused perhaps by a phase shift between the excited force and the movement. At the same time we can presume that the excited force is weakened, since the shape of the locus becomes smooth like that under an undamped free vibration. At the third stage Fig. 3 (c), the amplitude decreases gradually because of structural damping, and vortices with the excited force may vanish by themselves. After that these processes are repeated.

(2) Relationship between amplitudes and wind speeds

Before we obtain the relation between amplitudes and wind speeds, which is needed for the design of tower structure, we must estimate the fluctuating nature of the wind. At present we can not find a reasonable definition for wind speed containing fluctuation. However, supposing that the oscillation of the tower is caused by vortex shedding and is little influenced by the smaller scale fluctuating wind pressure, then the representative value of wind speed may be taken in the form of mean wind speed over a certain duration time.

The amplitudes for mean wind speeds averaged over one minute at the beginning of oscillation are shown in Fig. 4, which is not suitable for clarifying the relation between them because of scattered points. This means that the average duration time is not suitable for the oscillation of the tower.

We notice the fact that the transition periods as shown in Fig. 3 are characterized by the scale of the structure and the vortex shedding frequency. If the component lateral to the wind direction is taken out, the record of the amplitude looks like a "beat" whose period coincides with the transition periods. They were not constant but were subjected to variations of from 8sec to 100sec in the range of this measurement because of the differences in vortex shedding frequences due to changes of the mean wind speeds and the random fluctuation of the

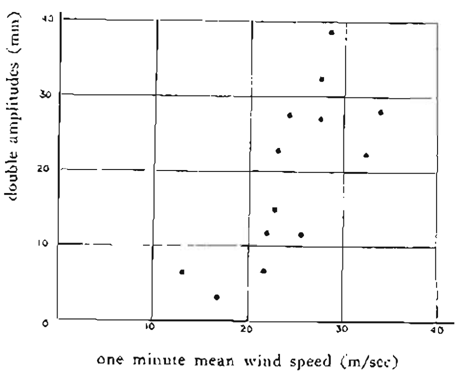

Fig. 4 The relation between amplitudes and wind speed averaged over one minute.

wind. However, because most of them had periods of about 40sec, we adopted 20sec as an appropriate duration time which contained the stage in Fig. 3 (a) and was long enough for the oscillation to develop fully. The relation between amplitudes and wind speeds averaged over 20sec is shown in Fig. 5, which gives a smooth curve. The curve in Fig. 5 is like the response curve of forced vibration with a resonance point at about 28m/sec, but it can not be regarded as a simple forced vibration.

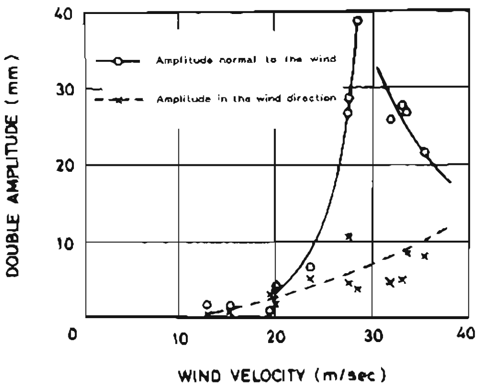

Fig. 5 The relation between amplitudes and wind speed averaged over 20 seconds.

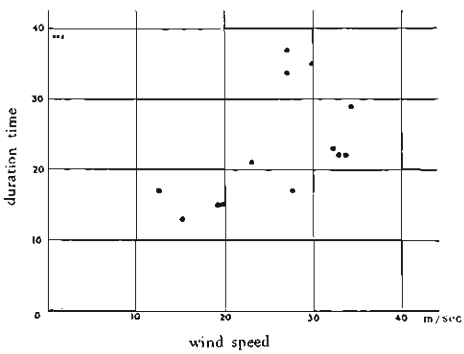

Fig. 6 The relation between duration time for maximum amplitudes and mean wind speed.

4. Discussion

M. Ozker and J. O. Smith said in their paper[2] on the oscillation of smoke stacks that the phenomena were a kind of self-excited motion because of the obscure generation of the vortex in a high Reynolds number region. According to their explanation, it is understood that the frequency of the structure coincides with one of free oscillation and that its lateral amplitude becomes extremely large. However, phenomena like a beat and the existence of a peak point of amplitude at a certain speed remain inexplicable facts.

In order to be clear about them we need to introduce the selfcontrolled periodic nature to the vortex generation, even if it is induced by the motion of the tower in the beginning. According to this inference, the time length of the transition periods must be decided only by wind speed, but in fact, they seem to be irregular as mentioned before. The duration time from the beginning to the full development of amplitude in each transition period was plotted versus the average wind speed in Fig. 6. It is considered that the scattering of these points is largely due to the random fluctuation of natural wind, and they seem to have a tendency for the duration time to become long at the same wind speed as when the maximum amplitude appears. This implies that beats are caused by small differences between the frequencies of the excited force and the tower motion. Thus, we can understand that the condition for the increase of amplitude is the continuation of the critical wind speed for several seconds during which oscillation takes place. We can infering from this point of view that a large scale of turbulence in natural wind has the effect of suppressing this kind of oscillation.

The Strouhal number calculated in this case is 0.15, which is less than the value usually indicated. The discrepancy may be ascribed to the following effects; the air flow is three dimensional, the measured wind speeds are the values at the top of the tower, and the obstacle is oscillating.

5. Conclusion

(1) Movement of the tower at the top

The top of the tower generally moves along an elliptic circuit, and its component lateral to the wind direction repeatedly increases and decreases.

(2) Time duration of average wind speed

Evaluation of the duration time for the average wind speed suitable for the structure should principally be decided from its scale and its momentum in oscillation, and 20seconds is suitable for this structure, in order to consider the correlation between amplitudes and wind speeds.

(3) The relationship between amplitudes and wind speeds

The amplitudes at the top of the tower were observed with regard to a 20 second mean wind speed up to 35.5m/sec. The peak value of the amplitude seems to exist at a wind speed of about 28m/sec.

(4) Exciting force induced by vortices

When a circular cylinder ceases to move, alternating forces do not act on it, since vortex shedding is not observed behind the cylinder. However, if its movement is small, then vortices which have a shedding frequency fitted to tower oscillation are generated. The amplitude increases by these vortices, but it is controlled after several seconds by the difference of phase between the motion of the tower and the exciting force. Hence, the amplitude decreases, and the vortices vanish too. Through a model test, we showed in another paper[3] that vortices appeared at a Reynolds number of about 10^5, if the cylinder continues to oscillate at the frequency associated with vortex formation.

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