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The body can be viewed from the next page.

Development of Highway Light Pole with Resistance to Wind Vortex-Induced Oscillations*

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1 Introduction

Highway light poles are installed not only along secondary roads but also on urban freeways, where they perform an essential safety function by providing consistent illumination. At the same, their use in densely populated areas imposes aesthetic requirements on their appearance, giving greater importance to non-functional factors such as shape and color. This tendency has become increasingly pronounced with the growing public insistence on quality of life, so that light poles are already considered a kind of "street furniture" in parks, plazas, and other such public places. On the other hand, light poles installed along freeways, where their visibility necessitates consideration of aesthetic factors, suffer severe oscillations as a result of wind and road surface vibration caused by heavy traffic, a fact which also must be given weight in their design.

This report discusses light poles for roads located under the severe wind conditions which occur at river crossings within harbors and across straits. The phenomenon of vibration due to Kármán-vortex-induced oscillation which these poles undergo in natural winds, is clarified, and a simple but effective impact damper is proposed. In order to investigate the effectiveness of the damper, fundamental tests were conducted using a vibration test machine. Tests were made to determine the movements of the damping weights, and a wind tunnel test was carried out using a full-size light pole. These tests demonstrated the effectiveness of the impact damper discussed below.

2 Vibration Tests on Light Pole

2.1 Outline of Tests

Vibration tests were conducted using a vibration test machine to clarify the vibrational characteristics of light poles, as well as the function and effectiveness of the damper. An 8-m-high full-size light pole with an octag-

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onal cross section was installed on the vibration test machine as shown in **Fig. 1** and vibration was induced with a sinusoidal wave. The dimensions of the test pole are given in the drawing. In these tests, basic vibrational characteristics, i.e., frequency in the resonant state, oscillation mode, etc., were first investigated. The effectiveness of the newly developed damper was investigated and factors necessary to obtain the optimum damping effect were considered.

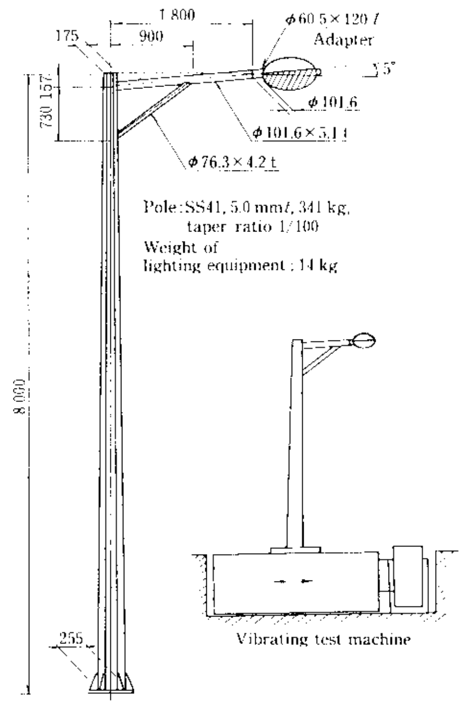


Fig. 1 Highway light pole with octagonal cross section and outline of vibration test machine

2.2 Investigation into Basic Vibrational Characteristics

As shown in **Table 1**, frequencies in the resonant state were determined with accelerometers installed at various points on the light pole by conducting a sweep test in which frequencies were varied under the constant force inducing vibration. Results of this test are summarized in **Table 2**. The relationship given by the following equation explains the phenomenon for the Kármán-vortex-induced oscillation:

$$S_t = ND/V \quad \cdots\cdots (1)$$

where S_t: 0.18 (a Strouhal number assumed by referring Yamada's report[1])
N: Frequency in resonant state
D: Typical diameter of pole
V: Wind velocity

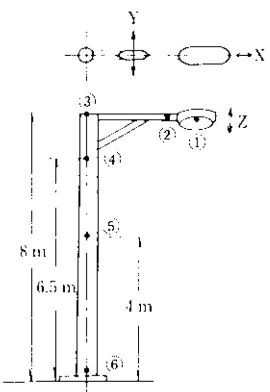
As shown in Table 2, the approximate resonant wind velocities for the light pole were determined by substituting the Strouhal value (0.18) into Eq. (1). These values were verified by the wind tunnel tests, which will be described later.

2.3 Damper

There have been many studies made on the oscillation induced by the Kármán vortex in tower-like structures. Methods of reducing this oscillation include (1) obtaining a resonant wind velocity higher than the

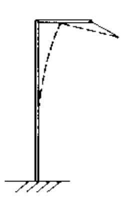
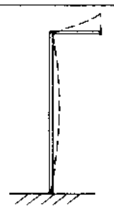
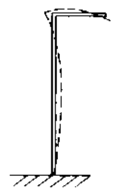
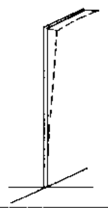
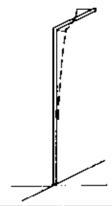
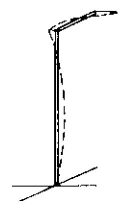
Table 1 Measurement of octagonal pole during vibration test

No.	Measured point	Measured item	Direction*1 Y	X	Z	Instrument for measurement
(1)	Lamp	Acceleration	○	○	○	Acceleration gage
(2)	Tip of arm	Acceleration	○	○	○	Acceleration gage
(3)	Top of pole	Acceleration	○	○		Acceleration gage
(4)(5)	Side of pole	Acceleration	○	○		Acceleration gage
(6)	50 mm Bottom of pole	Shear stress	○	○		Strain gage
		Bending stress	○	○		



*Y:Out of plane X:Inplane Z:Vertical

Table 2 Basic oscillation characteristics of octagonal-cross-section light pole

	Inplane oscillation mode			Out-of-plane oscillation mode		
	1st	2nd	3rd	1st	2nd	3rd
Oscillation mode						
Frequency in the resonant state (Hz)	2.9	12.3	22.5	2.9	7.3	20.8
Resonant wind velocity calculated (m/s)	3.5	14.7	25.6	3.5	8.7	24.8

design wind velocity by increasing the section stiffness of the structure, (2) reducing the amplitude of vibration by increasing the mass of the structure, (3) reducing the response magnification by raising the damping coefficient of the structure, (4) lowering the vibration energy by installing dampers to reduce the vortex-induced oscillation force, and (5) controlling oscillation aerodynamically by preventing the formation of the Kármán vortex or interrupting its cycle, which is accomplished by placing protrusions on the surface of a structure or changing its cross sectional shape. For the light poles discussed in this study, it is necessary to adopt a damping method that can be applied to as wide a range of wind velocities as possible. In addition, there are aesthetic problems, adaptability to various designs and limitations of installation space. In view of the foregoing, the damping method is considered to provide the most realistic solution. It was decided therefore to modify and apply the type of impact damper already proven effective with industrial equipment. The impact damper developed is shown in **Fig. 2**. Because it must be inserted in an elongated light pole structure, the container is provided with multi-layered cells and a steel ball or balls of appropriate mass is inserted in each cell as a damping weight. The steel balls move in synchronization with the oscillation of the light pole and collide with the casing, reducing the external force causing oscillation. To weaken the oscillation energy due to the impact of the damping weights, it is necessary to design the damper to obtain the maximum impact force under given conditions. For this purpose, the following must be considered:

(1) Optimum mass of damping weights.
(2) Size of and material used for damping weights.
(3) Clearance allowed for movement of damping weights.

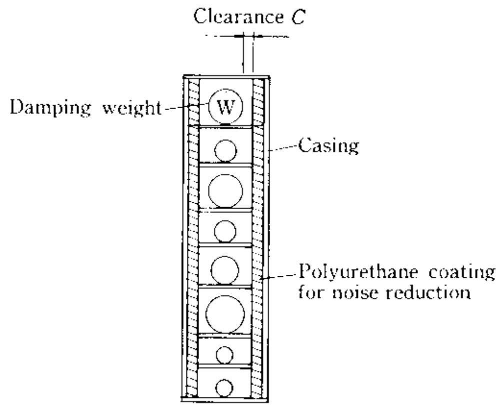


Fig. 2 Impact damper using steel balls

(4) Rigidity of the container, which affects the restitution coefficient.

The following understanding has been obtained from studies[2-5] conducted to date on impact dampers:

(a) When a damping weight moves regularly in synchronization with the oscillation of the structure, the larger the clearance, the greater the damping effect.
(b) When the clearance is constant, the higher the mass ratio of the structure to the damping weight, the greater the damping effect.
(c) The larger the restitution coefficient of the surface with which the damping weight collides, the greater the damping effect.

The light pole discussed in this study, however, is an elongated structure, as mentioned above, and the impact damper must be installed in a narrow space. The number of degrees of freedom in the selection of parameters therefore is not always large and there are many restrictions. For this reason, tests were conducted to clarify the basic vibrational characteristics of the movement of the damping weight in order to determine appropriate values for the design elements (1) to (4) above.

2.4 Basic Characteristics of Damping Weight

In this study, the impact damper is generally installed in a place where the amplitude is large in the basic oscillation modes shown in Table 2. For aesthetic reasons, however, the light pole cross section usually decreases gradually from the bottom to the top, where the light is fastened, limiting the space available for the installation of the impact damper at the top of the pole and thus the degree of amplitude possible. Based on a consideration of the oscillation modes shown in Table 2 and the criteria for installation of the impact damper, it was installed near the top of the pole for the first inplane oscillation mode and the first and second out-of-plane oscillation modes, and near the middle of the pole for the second and third inplane oscillation modes and the third out-of-plane oscillation mode. The cross section near the top of the pole, which depends on the height of the pole, is often no more than 100 to 150 mm in diameter. In addition, it is necessary to provide space for power cables to the lighting fixture at the tip of the arm. The outer diameter of the impact damper is therefore limited to about 50 to 70 mm.

The material for the damping weight should have a large mass and a high restitution coefficient in order to provide the maximum impact force within the limited space described above. It was decided to use steel balls based on considerations of workability and economy. Steel balls of the type normally used as bearings were adopted. To investigate the effect of the diameter of the balls and the clearance on the impact force, the device shown in **Fig. 3** was developed. The impact force was determined at natural frequencies in each oscillation mode given in Table 2 using this device installed on an impact test machine.

Impact forces should be expressed in the form of an impulse by the time integration of obtained impact waveforms. However, since the duration of the time of action of impact forces is very short (about 10 to 15 ms) and the purpose is to determine approximate values of impact force, maximum values obtained from the outputs of load cells were used without correction. The results of impact force measurements at natural frequencies of 2.8, 7.2 and 19.9 Hz are shown in **Fig. 4**. The maximum measured impact forces are shown in the figure, although impact forces vary considerably depending on the conditions under which the steel ball collides with the load cell. The surface of the steel ball was plated with chromium and the container surface with which the steel ball collides had mill scale. This condition was used in anticipation of the deterioration of the friction surface of the impact damper due to corrosion during service. It was determined, however, that impact forces changed little within the scope of this experiment, even with the polished surface and slightly corroded surface used. As is apparent from Fig. 4, the steel ball normally moves in synchronization at the natural frequency of 2.8 Hz for the first oscillation mode. In principle, the larger the mass of the steel ball, the larger the impact force will be, but under actual conditions, the range of clearance which permits synchronous movements is greater with a small steel ball. The same applies to synchronous movements at a

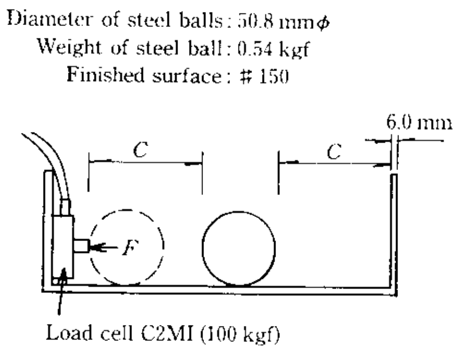


Fig. 3 Basic experiment set up for movement of steel ball and measurement of impact force

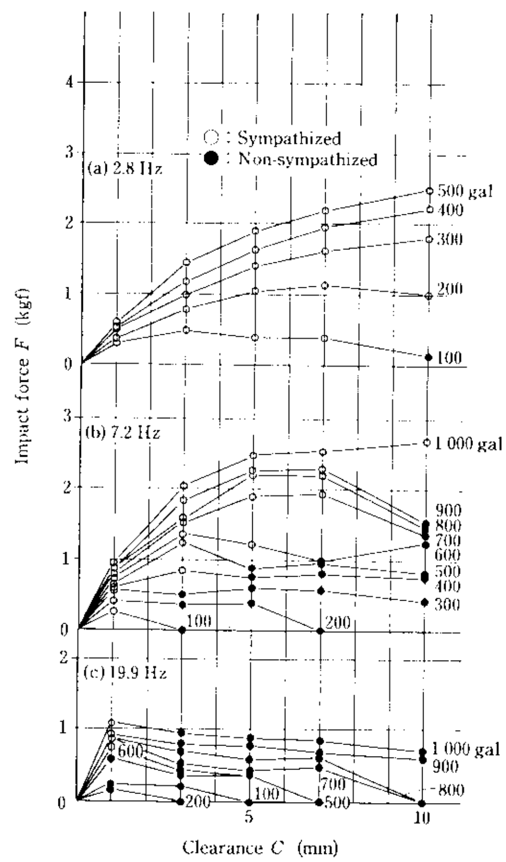


Fig. 4 Relationship between impact forces and wall distance

natural frequency of 7.2 Hz in the second out-of-plane oscillation mode. The range of clearance which permits synchronous movements is narrow, however, when the external force causing oscillation is small, and becomes very narrow, less than 3 mm, at 19.9 Hz, which corresponds to the third out-of-plane oscillation mode. It is, therefore desirable to use large steel balls and clearances for the first oscillation mode and small ones for the latter oscillation modes.

It is necessary to select an effective impact damper on the basis of these findings. In Table 2, the third oscillation mode, which occurs at resonant wind velocities of about 25 m/s, is regarded as a special case and is excluded. The first and second out-of-plane oscillation modes, which are considered to occur at high frequencies, were selected as objects of damping. Based on a consideration of space restrictions, the container for the damper was made with a square cross section 60 mm to the side and of a 2.3-mm-thick steel sheet. In addition, it was decided to use steel balls 50.8 mm in diameter in order to obtain a high impact force with a small number of steel balls because the effective space of the cell is 55.4 mm, the mass of damping weights is generally about 1 to 5% the mass of the vibrating body, and because the damper should have a short length.

2.5 Damping Effect of Impact Damper

In order to investigate the damping effect of the impact damper described above (container size 60 mm × 60 mm × 2.3 mm$t$, steel ball 50.8 mmϕ and 0.539 kg, clearance 4.6 mm), it was attached to the light pole shown in Fig. 1 and the pole was fixed with four bolts to the vibration test machine through a base plate using the same procedure as with the vibration tests conducted to investigate basic vibrational characteristics. The damper was installed at the top of the light pole and the number of damping weights was a maximum of 13 (mass ratio of the damping weights to the pole: about 2.8%). The effect of the mass ratio on damping was investigated using various numbers of weights. Wind-induced oscillation forces are imposed-forces distributed in the direction of the height of the light pole, while simple induced forces from the bottom end of the light pole are generated by the vibration test machine. It is not always possible, therefore, to accurately evaluate vibration behavior under actual conditions. In addition, oscillation forces induced in the resonant state are not clear. Therefore, the vibration tests were conducted for various forces causing oscillation for each natural frequency. The damping effect was great at less than 5 gal for the first inplane oscillation mode and at less than 20 gal for the second inplane oscillation mode. It was also great at less than 10 gal for the first out-of-plane oscillation mode and at less than 25 gal for the second out-of-plane oscillation mode.

Damping effects for these cases are shown in **Fig. 5**. From this figure, the higher the mass ratio, the higher

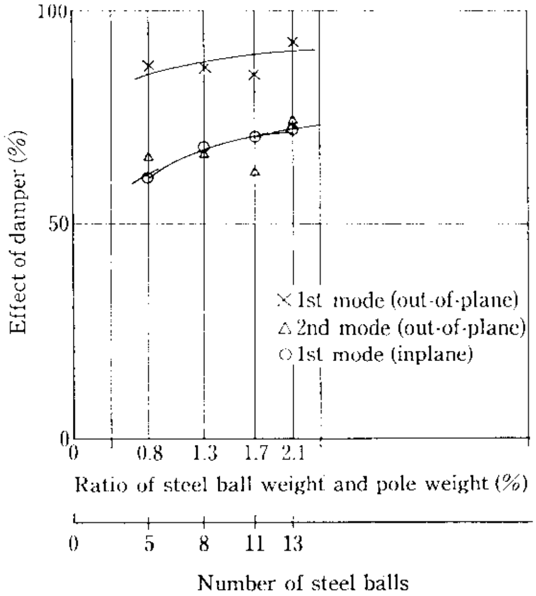


Fig. 5 Damping effects of the devised impact dampers (50.8 mmϕ steel ball)

the damping ratio. Maximum effectiveness is obtained with this damper at a mass ratio of about 2.1%. The damping ratio is about 90% for the first out-of-plane oscillation mode and 70-80% for the second out-of-plane oscillation mode and the first inplane oscillation mode. Normally, the damping effect in out-of-plane oscillations is greater for the first oscillation mode than for the second oscillation mode, while the damping ratio for the first inplane oscillation mode is almost the same as that for the second out-of-plane oscillation mode. Because the arm with the light undergoes flexural vibration in the same plane to a greater extent for inplane oscillations than for out-of-plane oscillations, the oscillation energy is large and damping is difficult, which seems to explain the above-mentioned difference in the damping effect.

3 Wind Tunnel Tests

After the vibration tests, wind tunnel tests were conducted to investigate the vibrational characteristics of the light pole in wind and to verify the effect of the damper selected based on the vibration test. The same light pole used in the vibration tests was used. A large wind tunnel with an exit cone size of 10 m × 3 m was used because the size of the pole tested was close to actual size.

3.1 Outline of Tests

The main items measured in the tests included:

(1) Vibrational characteristics of the light pole in wind, i.e., displacement or acceleration responses to structural damping and wind velocity.

(2) Effects of each damper.

Test conditions are shown in **Table 3**. Based on the assumption that the wind direction is at right angles to the axis of an actual bridge, the inplane direction of the light pole was selected as the wind direction.

Wind tunnel tests were divided into preliminary tests conducted without wind and regular tests with wind. For the preliminary tests, an electromagnetic damper was used as an exciter to reconfirm the oscillation modes. Three types of structural damping (logarithmic decrement values) were established by regulating the electromagnetic damper and response values to the respective oscillation modes were measured. In the regular tests, the relationships between wind velocity, acceleration, and displacement responses of the light pole in wind were investigated. The wind velocity ranged from 1 to 25 m/s. The impact damper was installed in an optimum position for the modes in which vortex-induced oscillation was observed, as with the basic tests described in Sec. 2.5 using a vibration test machine. The conditions for this wind tunnel test are shown in **Photo 1**.

Table 3 Conditions of wind tunnel test

Type of damper	No. of test levels		Type of test	No. of test cases
	Wind direction	Logarithmic decrement		
No damper	1	3	V-A test	3
Steel balls	1	1	V-A test	1

Photo 1 Overview of wind tunnel test of octagonal-cross-section light pole

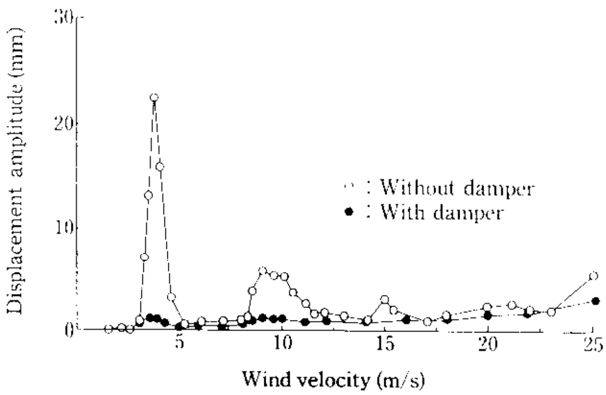


Fig. 6 Effect of wind velocity on the displacement amplitude of the top of the pole

3.2 Results of Tests

In this study, results obtained for an octagonal pole are described. Displacement amplitudes at the top of the pole for various wind velocities are shown in **Fig. 6**. The first out-of-plane oscillation mode was observed for $V \fallingdotseq 4$ m/s, and the second out-of-plane oscillation mode at $V \fallingdotseq 9$ m/s. Furthermore, there are indications that the third out-of-plane oscillation mode develops at $V \fallingdotseq 25$ m/s. Oscillation waveforms were separated for each of the oscillation modes using an analog filter. As a result, it was found that at $V = 25$ m/s, the displacement amplitude of 5.3 mm at the top is a combination of multiple oscillation modes comprising the first out-of-plane oscillation mode with an amplitude of 2.9 mm, the second out-of-plane oscillation mode with an amplitude of 1.8 mm, and the third out-of-plane oscillation mode with an amplitude of 0.8 mm. In this case, the first inplane oscillation mode has a large amplitude of 4.0 mm. It was also found that in the high wind velocity range, not only oscillations due to the Kármán vortex but also a complex oscillation mode occur even if the wind in the wind tunnel is disturbed slightly. For the first and second out-of-plane oscillation modes, the Strouhal number was calculated from the resonant wind velocities and oscillations; $S_t = 0.16$ to 0.17. These values were almost the same as the data in measurements by Yamada et al.[1]

The relationship between the wind velocity and the acceleration at the end of the pole arm (where the light is attached) is shown in **Fig. 7**. The acceleration amplitude shows a maximum value in the second out-of-plane oscillation mode. The acceleration in the third out-of-plane oscillation mode was about 295 gal at $V = 25$ m/s.

Displacement and acceleration amplitudes when a steel ball impact damper was installed are represented by black circles in Figs. 6 and 7 respectively. The displacement at the top of the pole is about 1/20 for the first

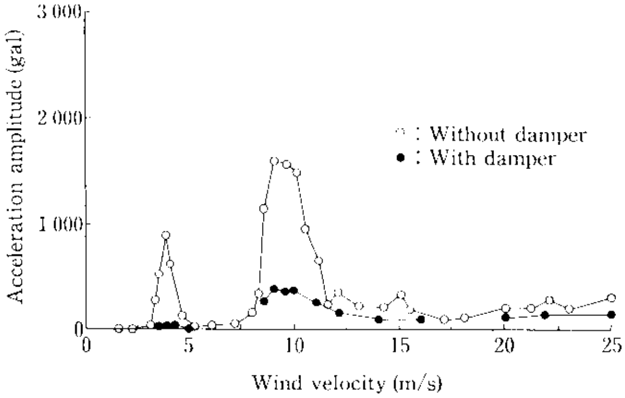


Fig. 7 Effect of wind velocity on the acceleration amplitude at the tip of the arm

out-of-plane oscillation mode and about 1/5 for the second out-of-plane oscillation mode. The acceleration at the tip of the arm was about 1/25 for the first out-of-plane oscillation mode and about 1/4 for the second out-of-plane oscillation mode, indicating that effective damping was obtained in both cases.

The relationship between structural damping (logarithmic decrement value) and the amplitude due to vibration is shown in **Fig. 8**. Oscillations in the first and second out-of-plane oscillation modes are considerably smaller when the logarithmic decrement value is 0.02 or more. Logarithmic decrement values when an impact damper is installed are given in **Table 4**. Higher logarithmic decrement values than when a damper was not installed were measured, thus demonstrating that the effectiveness of the damping device.

Incidentally, the same damping effects observed with the octagonal pole were also seen with a round pole in a test conducted by the authors.

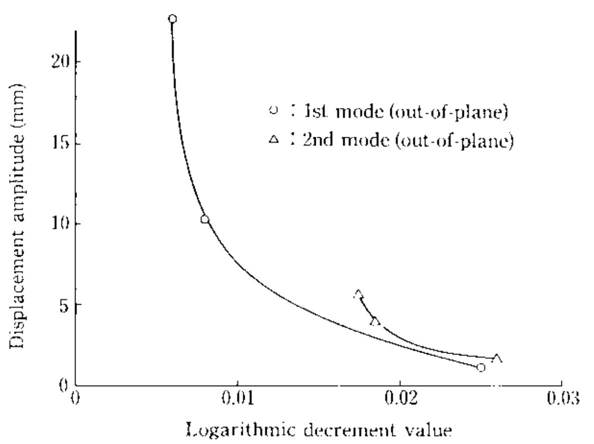


Fig. 8 Effect of logarithmic decrement on the displacement amplitude at the top of the pole

Table 4 Logarithmic decrement value

Mode	Without damper	With ball damper
1st deg.	0.004	0.06
2nd deg.	0.01	0.04

4 Design of Damper

Based on the effectiveness demonstated by the impact damper, a practical device was developed. The design procedure is shown in **Fig. 9**. If structural conditions such as the dimensions of the light pole, weight of the

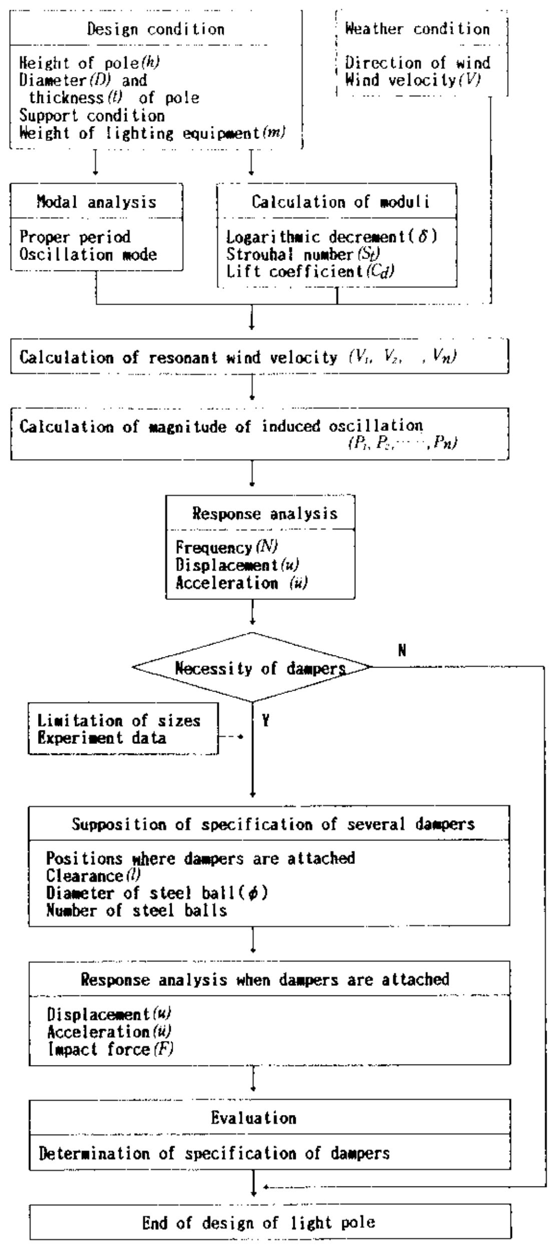


Fig. 9 Design flow chart for light pole with impact damper for effect of wind

lighting equipment, and support conditions for the pole, and weather conditions such as wind direction and velocity are given, it is possible to execute eigenvalues analyses. As a result, the natural frequency, natural period, and oscillation mode for the free movement of the pole can be determined. If the natural frequency, the cross section, and outside diameter of the pole are given, then S_t, N and D can be calculated from Eq. (1), and the resonant wind velocity can be obtained. For poles with a special cross-section, it is necessary to determine the Strouhal number S_t by conducting a wind tunnel test. If the resonant wind velocity is given, it is possible to judge whether Kármán-vortex-induced oscillation occurs, considering the installation conditions for the light pole and the maximum design wind velocity based on weather conditions or customer specifications. For a light pole with a Strouhal number of about 0.1 to 0.2, the typical diameter ranges from 100 to 200 mm, and the natural frequency of the first- to third-mode oscillations is 1 to 20 Hz. Therefore, Kármán-vortex-induced oscillation occurs at a wind velocity of about 20 m/s even in the third oscillation mode in the resonant state. For this reason, it is usually necessary to examine the behavior of Kármán-vortex-induced oscillation. Response analysis is possible because Kármán-vortex-induced oscillations is a forced oscillation due to variable lift generated periodically. In this case, it is necessary as a precondition that the lift coefficient C_L under the induced external force given by the following equation be determined in advance:

$$L(t) = \int_0^h \frac{1}{2} \rho V^2 D C_L e^{i\omega_n t} dh \quad \cdots\cdots\cdots\cdots (2)$$

where $L(t)$: Lift

ρ: Density of air

h: Height of light pole

ω_n: n-th oscillation period

Studies[6-9] have been made for some time on the value of C_L, and many relate to tower-like structures such as chimneys and smokestacks. The following equation is considered valid when Kármán-vortex-induced oscillation occurs and the light pole is moving in synchronization with the wind:

$$C_L = \frac{8m\pi N^2 \delta}{\rho V^2 l} \left(\frac{a}{D}\right) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where m: Mass of vibrating body (light pole)

δ: Logarithmic decrement

a: Displacement amplitude

If Eq. (3) can be applied to a light pole and the values obtained in the wind tunnel tests in Sec. 3.2 are used, the lift coefficient for a light pole with an octagonal cross section is about 0.3. Many points concerning C_L remain unclear, however, and precise wind tunnel tests are necessary for rational design.

If response analysis is made using induced forces calculated by Eq. (2), various response values such as displacement of the light pole due to vibration can be determined. A typical analysis method is that proposed by Y. Ogata et al.[10] If various responses are found, the damping force can be determined by repeating response calculations and by considering a damping force of any magnitude in any position in the same manner as was used with the above-mentioned induced external force, so that allowable displacements corresponding to damping ratios can be established. If the damping force is determined, then the number and size of damping weights, clearance, and other factors can be calculated by considering the restrictions on space available for the installation of the damper, because the relationship between the impact force and the clearance of the damping weights can be obtained experimentally, as mentioned earlier.

5 Conclusions

In order to reduce the Kármán-vortex-induced oscillation of highway light poles, typical vibrational characteristics of such poles were first investigated and an impact damper was then developed. Basic experiments were conducted using a vibration test machine to investigate the effectiveness of this damper, with positive results. The damper was then tested in a large wind tunnel using a full-size pole. The following results was obtained from these basic and mock-up tests:

(1) Kármán-vortex-induced oscillation can be reduced to a considerable degree by using an impact damper having cells arranged in one direction, as developed in this study.

(2) With the impact damper installed on a pole with an octagonal cross section, it is possible to reduce the amplitude of vibration 90% for the first out-of-plane oscillation mode (resonant frequency 2.9 Hz) from that when no damper is installed. This was evident from both basic and wind tunnel tests.

(3) As in the first out-of-plane oscillation mode, the effective damping is also obtained in the second out-of-plane oscillation mode (resonant frequency 7.1 Hz). This damping effect however is somewhat smaller than in the first oscillation mode, because the oscillation has a considerably smaller amplitude under large oscillation energy. A reduction of about 70 to 80% in terms of absolute value is possible.

(4) From tests on the movement of damping weights, it was found that if the damping weights are steel balls of the same weight, the range of clearance which permits synchronous movements with the container of the damper is very great for the oscillations caused by small external force, and, the larger the clearance, the larger the impact force will be. For oscillations caused by great external force, however, the clearance range to resonance is narrow.

(5) In designing a damper, it is necessary to select relatively large damping weights and clearances for the

oscillations caused by small external force, and relatively small damping weights and clearances for oscillations caused by great external force. (although in the latter case, the number of damping weights is increased.)

(6) The results of wind tunnel tests using full-size light pole with an octagonal cross section reveal that the lift coefficient of air, C_L, which affects the external force of forced oscillation to which the pole is subjected is about 0.3. This value is almost the same as that obtained with a round pole in a recent study.

It was revealed from these results that Kármán-vortex-induced oscillation can be reduced considerably in a light pole with the same rigidity as the octagonal pole used in this study by installing an impact damper. In the future, however, it is necessary to thoroughly reduce the collision noise from the impact damper developed in this study. Using a simple method adopted at present, the collision surface is coated with resin. It is also necessary to develop an effective method of installation to meet space limitations. Further, research and development in corrosion prevention is also necessary in order to improve durability. The authors would like to report these items separately.

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