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EFFECTS OF DEAD WEIGHT ON AERODYNAMIC STABILITY OF LONG-SPAN SUSPENSION BRIDGES

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In modern civil engineering structures which tend to be light and slender, the problem of aerodynamic stability in wind has gained increasing importance. Long-span suspension bridges are typical among such structures. If streamlined box girder is used as stiffening frame, its small dead load can be advantageous in view of economy, compared with the use of stiffening truss. However, it is needless to say that various kinds of wind-induced vibrations shall be also examined in this case.

In the present paper, the effects of dead weight on the aerodynamic stability of suspension bridges stiffened by streamlined box girder are investigated, and it was found that the increase of dead weight could improve the resistance of the structure against wind, without noticeable reduction of natural frequencies. Furthermore, based on sectional model wind tunnel tests, the effects of suppressing wind-induced vibrations by dead weight are examined. Finally, for model suspension bridges preliminary designed, the effects of dead weight are concretely examined to obtain information on the application to design for aerodynamic stability.

1. INTRODUCTION

The stiffening frames of aerodynamically stable suspension bridges may be classified into trussed girders and streamlined box girders. Although the latter is said to attain lighter design as compared with the former, in Japan, truss-stiffened types have been used for various reasons. However, shallow box girder has been adopted for the first time in Ohshima Bridge now under construction, in view of appearance and economy[1]. This is, therefore, surmised to trigger the interest in streamlined box girders for suspension bridges.

In case of the conventional stiffening trusses, the govering aerodynamic instability is usually stall flutter. On the other hand, when streamlined box girders are used, coupled flutter under horizontal wind, stall flutter under relatively large inclined wind, and vortex excitation for relatively bluff cross section may occur. Furthermore, the necessity for examining buffeting due to the turbulence of approaching wind is also considered to increase.

In order to suppress the above-mentioned vibrations induced by wind, various aerodynamic and mechanical means have been proposed[2]. In view of economy and feasibility, it must be wise to adopt aerodynamically stable section from the initial stage of designing. These situations are similar in cable-stayed girder bridges. However, even though aerodynamic means are certainly effective, they cannot be fully used in actual structures on account of various restrictions such as appearance and functions, etc. Accordingly, the use of mechanical means or of the both means may be necessitated in many cases.

Hitherto, the use of mechanical means has been rare in suspension bridges[2]. One of the examples is an

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inclined hanger system in Severn Bridge to increase the rigidity of the suspension bridge and to expect the hysteresis damping, but recently various problems have been pointed out[3),4)] for this bridge. On the other hand, as already indicated by A. Hirai and the second author of this paper, the dead weight contributes to the rigidity of a suspension bridge[5)]. Therefore, if the dead weight can be increased, with streamlined cross sections kept the same, to such an extent as to have an economical advantage compared with the stiffening truss type, and the natural frequencies are hardly affected, then it would be significant to discuss the effect of dead weight on the aerodynamic stability of a suspension bridge, as one of mechanical means. Meanwhile, if the dead weight increases, the horizontal component of the cable tention becomes large in proportion to it, and generally the polar moment of inertia of the structure increases. Therefore, when the effects of dead weigtht are examined, all of these must be taken into account.

Thus, in this paper, at first, with respect to the nondimensional characteristic parameters which govern the vertical and torsional vibrations of a suspension bridge, natural frequencies and modes are parametrically analyzed to discuss the effect of dead weight on the dynamic characteristics of suspension bridges. Then, sectional model wind tunnel tests were conducted for different types of cross sections to discuss the effect of mass and polar moment of inertia on the vortex excitation and flutter induced by wind. Finally, with preliminary designed prototype bridge having streamlined box girder, the dead weight is increased to such an extent as not to exceed the dead weight of the truss-stiffened type in order to investigate the changes in the frequencies of lower modes of vibration, and the critical wind velocity of coupled flutter is calculated by Bleich's theory. Then, by using the unsteady aerodynamic forces obtained from the sectional model tests, the time series respones of torsional vortex excitation were calculated to obtain basic data concerning the effects of dead weight on the aerodynamic stability of suspension bridges.

2. PARAMETRIC ANALYSES OF NATURAL FREQUENCIES AND MODES OF SUSPENSION BRIDGES

(1) Method and assumptions of analyses

For the sake of simplicity, the analytical method used here is based on the linearized deflection theory[6),7)] where the cable tension is assumed constant, and the rigidity of towers as well as the influence of hanger inclination are neglected. This treatment involves little problem in preliminary calculation of the dynamic characteristics of lower vibration modes which are important for discussing the aerodynamic stability.

If the dead weight of a suspension bridge increases, the horizontal component H_W of the cable tention increases in proportion to it. Therefore, the rigidity of the suspension bridge is increased. However in an actual design, the sectional area A_C of the cable is also increased, and this makes the dead weight w and polar moment of inertia I_θ larger. As a result, the characteristics of natural vibrations are considered to be complicated. Therefore, it was decided to evaluate the first symmetric and asymmetric mode of natural vibrations respectively, with respect to the nondimensional, characteristic parameters. In this paper, 3-span two-hinged suspension bridges were selcted for discussion, considering the type usually used for long-span road suspension bridges. The nondimensional characteristic parameters shown in (2) were calculated according to the reference 7).

(2) Nondimensional, characteristic parameters

a) Vertical vibration

The first asymmetric mode of vibration is dependent on the following nondimensional characteristic parameter.

$$P_{1,v}=l\sqrt{\frac{H_w}{EI}}, \qquad (1)$$

where l=length of center span ; H_W=horizontal component of the cable tension ; EI=flexural rigidity of the stiffening frame. On the other hand, in the case of the symmetric modes of vibration, the following four nondimensional characteristic parameters shall be considered in addition to the above parameter by Eq.

(1):

$$P_2=\frac{E_C A_C}{L_E}\frac{f^2}{H_w l},\quad P_3=\frac{l_1}{l},\quad P_4=\frac{w_1}{w},\quad P_5=\frac{I_1}{I} \quad\cdots\cdots (2)$$

where E_C=modulus of elasticity of the cable; A_C=cross sectional area of the cable; f=cable sag in the center span; L_E=virtual length defined by the integral $\int_0^L (ds/dx)^3 dx$, in which ds is a differential element along the cable curve, and L=total length of the stiffening frame over all spans; w=dead weight of the bridge per unit length; I=vertical moment of inertia of the stiffening frame; index " 1 " represents the quantity at side spans. Furthermore, the natural circular frequency ω_η can be expressed nondimensionally as follows:

$$\omega_\eta^*=\omega_\eta\sqrt{\frac{wl^4}{gEI}}, \quad\cdots\cdots (3)$$

where g=gravity acceleration.

Of the above five parameters, $P_{1,V}$ and P_2 are usually distributed within the following respective ranges in a long-span suspension bridge exceeding 500 m in center span[8]:

$P_{1,V}$: 8~50, P_2: 1.5~2.5

b) Torsional vibration

The first asymmetric mode of vibration is dependent on the following nondimensional characteristic parameter, when the influence of warping rigidity can be neglected:

$$P_{1,T}=\frac{H_w}{GJ}\left(\frac{b}{2}\right)^2, \quad\cdots\cdots (4)$$

where GJ=torsional rigidity of the stiffening frame; b=distance of the cables. The symmetric modes of vibration are related also to the three nondimensional characteristic parameters of P_2, P_3 and P_4 in Eq. (2), in addition to the above parameter by Eq. (4). Furthermore, the natural circular frequency ω_ϕ is made nondimensional as follows:

$$\omega_\phi^*=\omega_\phi\sqrt{\frac{I_\theta\cdot l^2}{GJ}}, \quad\cdots\cdots (5)$$

where I_θ=polar moment of inertia of the suspension bridge per unit length.

Parameter $P_{1,T}$ is usually distributed within the following range in case that center span exceeds 500 m[8]:

$P_{1,T}$: 0.05~0.67

(3) Results of calculation and discussion

Considering the ranges of nondimensional characteristic parameters shown in the previous section and the values in model suspension bridges shown in 4., it was decided to use the valuses of following ranges for the nondimensional characteristic parameters of vertical modes:

$P_{1,V}$: 5~55, P_2: 1.0~3.0, P_3: 0.3, P_4: 1.0, P_5: 1.0

For the torsional modes, the values of the following range were used

$P_{1,T}$: 0.05~0.65,

and for the other three nondimensional characteristic parameters of P_2, P_3 and P_4, the same values as used for vertical modes were employed. The nondimensional natural circular frequencies of vertical and torsional vibrations obtained are shown in Figs. 1 and 2, respectively. The figures also indicate the results of model suspension bridges in 4., but their discussion is made in 4.

At first, vertical vibrations will be examined. From Fig. 1, it can be seen that, for $P_{1,v}$ larger than 10, the first asymmetric mode gives the lowest natural frequency. Furthermore, in this range, the nondimensional natural circular frequencies ω_η^* of both the first symmetric and asymmetric mode increase almost linearly with $P_{1,v}$ and the ratio $\Delta\omega_\eta^*/\Delta P_{1,v}$ of the respective change rates of ω_η^* and $P_{1,v}$ is only somewhat smaller than 1.0 when $P_{1,v}$ varies from 10 to 20. The dead weight w of a suspension bridge per unit length is proportional to the horizontal component H_W of the cable tension. Therefore, it is surmised that the first asymmetric natural frequency of an actual bridge is little reduced even if the dead weight increases in the range of the nondimensional characteristic parameters examined here. Also for the first symmetric natural frequency, a similar discussion is allowed since P_2 changes little when the sectional area A_C of the cable increases almost in proportion to the magnitude of the horizontal component H_W of the cable tension.

As far as the torsional mode of vibration is concerned, from Fig. 2, it can be seen that when P_2 is smaller than about 2.1, the lowest torsional frequency is that of the first symmetirc mode in the whole range of $P_{1,T}$ and that, even in the case of $P_2=3$, the same finding can be applied if $P_{1,T}$ is smaller than about 0.38. The ratio $\Delta\omega_\phi^*/\Delta P_{1,T}$ of the respective change rates of ω_ϕ^* and $P_{1,T}$ is larger for the first symmetric natural frequency than for the first asymmetric mode. Therefore, it can be said that the contribution of H_W by the dead weight is more remarkable for the first symmetric natural frequency. However, it must be noted that the contribution varies depending on the value of $P_{1,T}$. As mentioned before, if the dead weight w is increased, the horizontal component H_w of the cable tension increases in proportion to it. Furthermore, the sectional area A_c of the cable increases almost linearly to the increase of H_w, and therefore, the polar moment of inertia will also increase. In this connection, calculation of $\Delta\omega_\phi^*/\sqrt{\Delta P_{1,T}}$ was made, and it was found that this value was somewhat smaller than 1.0 when $P_{1,T}$ varied from 0.1 to 0.2. Therefore, in this range, when P_2 does not change with increasing the polar moment of inertia of cable, the first symmetric natural frequency which is the lowest is considered to reduce little. On the other hand, the nondimensional natural circular frequency sensitively changes according to the value of P_2. Therefore, when the center span sag f is lessened in order to increase H_w, P_2 becomes small, as can be seen from its definition, so that, the first symmetric natural frequency is expected to be reduced.

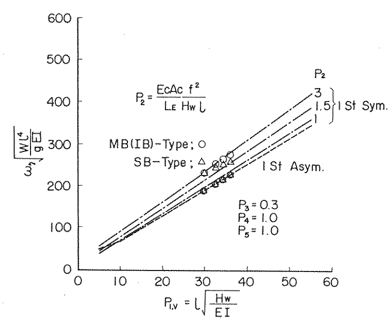

Fig. 1 Nondimensionalized Vertical Frequencies.

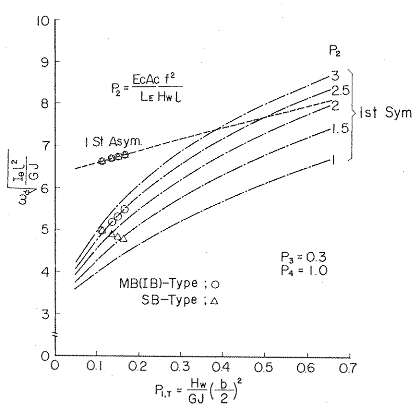

Fig. 2 Nondimensionalized Torsional Frequencies.

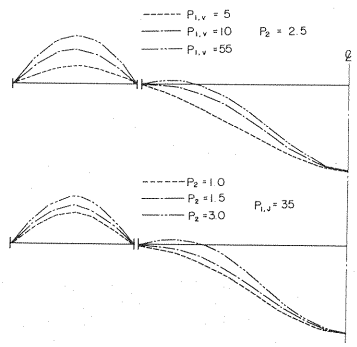

Fig. 3 Effect of Various Characteristic Parameters on lst Symmetric Mode Shapes of Vertical Vibration.

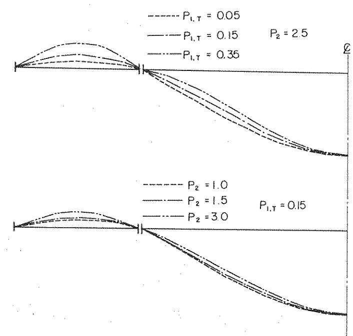

Fig. 4 Effect of Various Characteristic Parameters on lst Symmetric Mode Shapes of Torsional Vibration.

Finally, the influence of nondimensional characteristic parameters on the mode shape is discussed. When $P_{1,V}$ and P_2 are respectively changed, the first symmetric mode of vertical vibration changes as shown in Fig. 3, and when $P_{1,T}$ and P_2 are respectively changed, the first symmetric mode of torsional vibration changes as shown in Fig. 4. From these figures, it can be seen that nondimensional characteristic parameters delicately change the mode shape. Therefore, when the development of wind-induced vibration depends greatly on the amplitude, care must be taken for even a slight difference in the mode shape of vibration.

3. WIND TUNNEL TESTS WITH SECTIONAL MODEL

(1) Test models and testing method

The spring-mounted sectional model tests were conducted in the wind tunnel at the University of Tokyo. The linear scale of the models was 1/64 in view of the working section (1.8 m high×1.1 m wide) of the wind tunnel. Three types of sectional models as shown in Fig. 5 were prepared ;that is, a shallow rectangular cross section (MODEL Ⅰ) ; a shallow hexagonal cross section (MODEL Ⅱ) and a shallow hexagonal cross section with curbs and railings considering an actural bridge (MODEL Ⅲ).

The tests were mainly conducted at the angle of attack $\alpha=+5^\circ$ in uniform flow, intending to induce the relatively large aerodynamic response. Also some tests were conducted in turbulent flow at the angle of attack $\alpha=0^\circ$. Furthermore, for the cross sections similar to the flat plate as tested this time, the aerodynamic damping in still air cannot be disregarded. For this reason, the damping with the aerodynamic effect eliminated was considered as structural damping[9]. If the dead weight of a suspension bridge increases, the mass and polar moment of inertia respectively increase. The influences of dead weight (mass and polar moment of inertia) on aerodynamic instabilities are discussed in the following.

(2) Vortex excitation

When the vertical and torsional vibrations induced by wind are not coupled and their frequencies are equal to the corresponding natural frequencies in still air, the following mass-damping parameters, or Scruton numbers can be used as nondimensional parameters.

$$\text{Vertical vibration}: \frac{2m\delta_2}{\rho BD} \quad \text{Torsional vibration}: \frac{2I_\theta\delta_\theta}{\rho(BD)^2}$$

in which m and I_θ are the mass and polar moment of inertia per unit length, respectively, δ_η and δ_θ are the vertical and torsional structural logarithmic decrement, respectively, ρ is the air density, and B, D are the width and depth of the cross section, respectively. According to the definition, the Scruton numbers of vertical and torsional vibration in the cross section assuming an actual bridge (MODEL Ⅲ) are respectively about 6.5, if $\delta_\eta=\delta_\theta=0.02$[10] is used as the structural logarithmic decrement.

Thus, at first, the tests with MODEL Ⅰ was conducted in one degree of freedom in uniform flow at the angle of attack $\alpha=+5^\circ$. The results are shown in Figs. 6 and 7. From these figures, it can be observed that, as Scruton number increases, vertical and torsional responses became small and the wind velocity range which induces vibrations somewhat narrowed. However, in order to suppress the amplitudes of wind-induced vibrations to acceptable level, a very large Scruton number is required. Therefore, it does not seem to be feasible to suppress the vortex excitation caused in the flat rectangular cross section only by adjusting the mass and polar moment of inertia.

MODEL Ⅱ was set in two degrees of freedom in uniform flow at the angle of attack $\alpha=+5^\circ$, and Scruton number was made as samll as possible for conducting preliminary tests in order to get the basic properties of vortex excitation for a shallow hexagonal cross section. In this case, only torsional vortex excitation occurred. Therefore, for a suspension bridge having the stiffening girder with a shallow hexagonal cross section as tested this time, a special care may be required for vortex excitation in torsion.

The tests with MODEL Ⅲ were conducted in one degree of freedom for torsion in uniform flow at an angle of attack $\alpha=+5^\circ$. The results are shown in Figs. 8 and 9. On the abscissae in Fig. 9, polar moment of

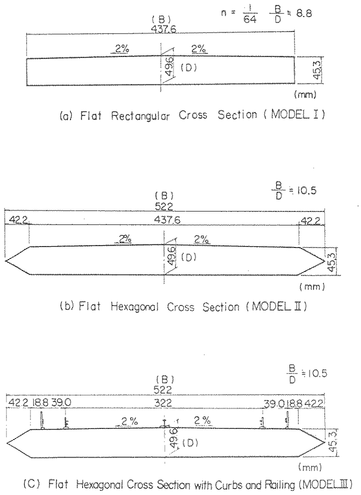

Fig. 5 Model Sections for Wind Tunnel Test.

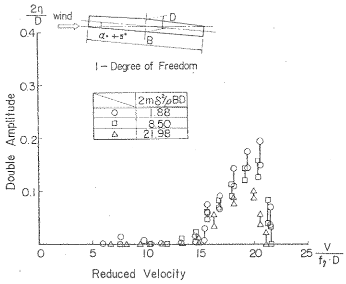

Fig. 6 Effect of Scruton Number on Vertical Response in Smooth Flow (MODEL I).

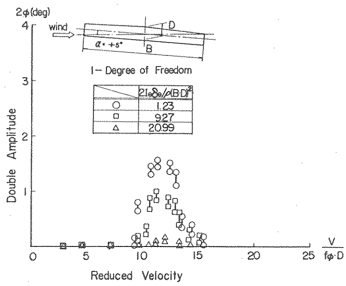

Fig. 7 Effect of Scruton Number on Torsional Response in Smooth Flow (MODEL I).

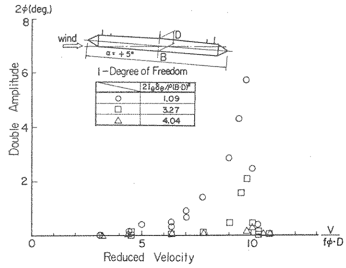

Fig. 8 Effect of Scruton Number on Torsional Response in Smooth Flow (MODEL III).

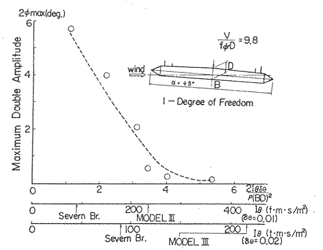

Fig. 9 Effect of Scruton Number on Maximum Torsional Response in Smooth Flow (MODEL III).

inertia obtained with the structural logarithmic decrement of an actural bridge assumed as 0.01 and 0.02 are plotted, and the values of Severn Bridge[11] with almost the same span are also shown, though its cross section is slightly different from the assumed bridge. From these Figures, it can be seen that the torsional response observed is very sensitive to the increase of Scruton number and that the increase of Scruton number allows the wind velocity range which induces vibration to be narrowed considerably in the range applicable for design. Then, with the angle of attack set at $\alpha=0^\circ$, similar tests were conducted in turbulent flow generated by grid, in which the intensity of turbulence I_u in the main flow direction was 11 % and the scale of turbulence L_X^u was 7.3 cm. The results are shown in **Figs.** 10 and 11. In this case, compared with the tests in uniform flow at the angle of attack $\alpha=+5^\circ$, the effect of Scruton number on the torsional response slightly decreases. However, it can be seen that Scruton number restricts amplitudes causing no practical problem similarly in the range applicable for design.

(3) Stall flutter

When vertical and torsional vibration is allowed in two degrees of freedom, it is expected that coupled flutter will occur for MODEL II (**Fig.** 5(b)), aerodynamic characteristics of which are like those of a flat plate, and that stall flutter will occur for MODEL I (**Fig.** 5(a)) with relatively bluff cross section. However, in the model tests, coupled flutter did not appear in the former within the wind velocity range of wind tunnel. Therefore, the discussion on this phenomenon will be made in 5. (3), and only stall flutter appeared in uniform flow at the angle of attack $\alpha=+5^\circ$ for MODEL I will be discussed here. With the structural logarithmic decrement kept almost constant, the polar moment of inertia was increased. The results of the tests are shown in **Fig.** 12. Also for a streamlined box girder type, stall flutter, the development process of which is very similar to that for the shallow rectangular cross section, is expected to appear under relatively large inclined wind. Therefore, the difference of cross sectional shape is not considered to be an essential factor in knowing stall flutter characteristics.

From **Fig.** 12, it can be seen that the effect of polar moment of inertia on stall flutter is recognized but is

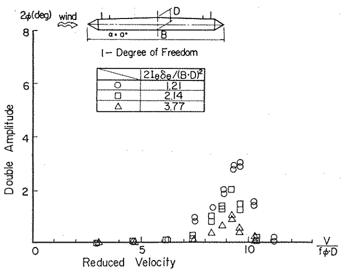

Fig. 10 Effect of Scruton Number on Torsional Response in Grid Turbulent Flow (MODEL Ⅲ).

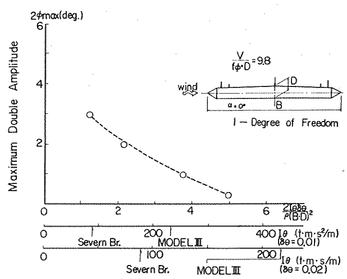

Fig. 11 Effect of Scruton Number on Maximum Torsional Response in Grid Turbulent Flow (MODEL Ⅲ).

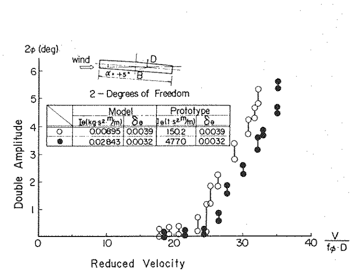

Fig. 12 Effect of Polar Moment of Inertia on Stall Flutter in Smooth Flow (MODEL Ⅲ).

not so remarkable. Therefore, when an actual suspension bridge is designed, the effect brought by the increase of polar moment of inertia should not be overestimated for stall flutter.

(4) Some additional explanation of wind tunnel test results and aerodynamic considerations

The torsional response of vortex excitation appeared in MODEL Ⅲ reacted very sensitively to the change of Scruton number. This might be caused by the reduction of unsteady aerodynamic force owing to the fairing attached as one of aerodynamic means. Aerodynamic means are very effective in reducing the unsteady aerodynamic force as observed in the above case. However, since this effect has certain limitation, the mass, polar moment of inertia and structural damping play also an important role for the structure that the vortex excitation can not be completely suppressed by the aerodynamic means. Among these physical quantities, structural damping can not be obtained by theoretical calculation, and have to be guessed from the full scale measurements with similar structures. On the contrary, the mass and polar moment of inertia, compared with structural damping, can be rather accurately calculated in the stage of design. For this reason, it seems that the mass and ploar moment of inertia of the structure are controling factors in aerodynamic design.

The buffeting due to the turbulence of natural wind also stirs up discussion recently concerned with serviceability and fatigue limit state. In the streamlined box girder type, vertical buffeting mainly comes into problem, but its accurate estimation is difficult because of technical problems in the wind tunnel tests, wind conditions and theoretical assumption in analysis. However, qualitatively speaking, as can be estimated from the buffeting theory[12], the increase of structural damping is not so effective, and it is known that the vertical buffeting greatly depends on the mass of the structure.

In a streamlined box girder type suspension bridge, coupled flutter is expected under horizontal wind, while stall flutter will be occured under inclined wind. As stated already, the effect of polar moment of inertia on the critical wind velocity of stall flutter was examined. However, it is expected that the angle of inclination of natural wind in such a high wind velocity range as to cause flutter is generally very small if the approaching wind is not affected by surrounding natural features[13]. Although there remain some unclear aerodynamic problems by atmospheric turbulence, in a streamlined box girder type suspension bridge, coupled flutter will be one of the most dominant instability. The critical wind velocity of coupled flutter of bridge deck can be presumed, as a first approximation, by applying the correction factor to the value from the Selberg's empirical formula[14]. According to this formula, the critical wind velocity of coupled flutter rises if the mass and polar mement of inertia become large, as far as the other conditions remain the same. However, even in suspension bridges with streamlined box girders under nearly horizontal wind, the quasi-coupled flutter as designated by Miyata and Okauchi[15),16] may be appeared depending on the details of the cross sections and frequency ratio, etc. of the bridge. Therefore, it will be necessary to check the flutter instability for respective prototype. Moreover, the effect of static deformation due to strong wind on flutter is anticipated[17], but it will be negligible in the case of streamlined box girders.

Judging from the above discussions, the dead weight in a suspension bridge having streamlined box girder acts effectively to reduce various kinds of wind-induced responses, and therefore is considered to be important factors for designing suspension bridges against wind.

4. AERODYNAMIC EXAMINATION OF MODEL SUSPENSION BRIDGES

(1) Model suspension bridges for calculation

Suspension bridges examined were 3-span, two-hinged suspension bridges with center span of 1 000m (a side to center span ratio of 0.3) stiffened with streamlined box girders. They were preliminarily designed according to the current specifications and standards[18] in Japan. The general view of the basic type (B-Type), is shown in Fig. 13. Further preliminary design was made with the same cross sections, by increasing the dead weight by use of materials not increasing the girder rigidity near the center of the box girder (MB-Type), and by applying at positions of 5 m apart from the center of box girder to make the polar moment of inertia larger than that of MB-Type (IB-Type). The additional dead weight was 2.8t/m/Br. for MB1-Type and 6.8t/m/Br. for MB 3-Type, and these were intended to be almost equal to the total dead weight of stiffening truss type suspension bridges with the orthotropic steel deck or reinforced concrete deck respectively which were designed under the same conditions. Furthermore, considering that the sag-span ratio may be slightly decreased to increase the rigidity of the entire suspension bridge system in an actual design, further preliminary design was conducted by changing the sag-span ratio to make the horizontal component of the cable tension to be equal to those of MB and IB-Types (SB-Type). The respective sectional values are shown in Table. 1. In the table, the respective types have the same girder rigidity, because their cross sections were governed by the minimum plate thicknesses requirements (steel floor plate ; 12 mm, bottom flange plate ; 10 mm).

(2) Natural frequencies

The natural frequencies of the respective model suspension bridges mentioned above were calculated by applying the linearized deflection theory. The natural frequencies of first symmetric and asymmetric modes of vertical and torsional vibration obtained by the analysis are respectively shown in Figs. 14 and 15. The nondimensional natural circular frequencies of vertical and torsional vibrations arranged according to nondimensional characteristic parameters are respectively plotted in Figs. 1 and 2.

At first, vertical vibration will be discussed. From Figs. 14 and 15, it can be seen that the first symmetric and asymmetric modes of vertical vibrations in SB-Type slightly increased according to the decrease of sag-span ratio. These results are convincing since the nondimensional natural circular frequency of vertical vibration shown in Fig. 1 gradually increased, even though P_2 increased almost constantly in MB-Type (IB-Type) and decreased in SB-Type.

As far as the torsional vibration is concerned, the natural frequency of first symmetric mode (the lowest torsional frequency of model suspension bridges) is aerodynamically most important. As can be seen Figs. 14 and 15, the natural frequency of first symmetric mode is almost independent of polar moment of

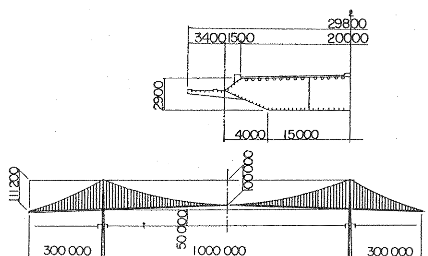

Fig. 13 General View (B-Type).

Table. 1 Types and Sectional Values.

(Per Bridge)

				Streamlined Box Girder						
		Type		Basic	Additional Mass Type			Sag Modification Type		
				B	MB1 (IB1)	MB2 (IB2)	MB3 (IB3)	SB1	SB2	SB3
		SAG RATIO		$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{11.5}$	$\frac{1}{12.4}$	$\frac{1}{13.4}$
Dead Weight	Main Cable	W_c	t/m	5.300	6.000	6.500	7.000	6.000	6.500	7.000
	Girder (empty)	W_f	t/m	10.083	10.083	10.083	10.083	10.083	10.083	10.083
	Additional Weight		t/m	0.	2.800	4.800	6.800	0	0	0
	Pavement		t/m	3.117	3.117	3.117	3.117	3.117	3.117	3.117
	Total	W	t/m	18.500	22.000	24.500	27.000	19.200	19.700	20.200
Polar Moment of Inertia		I_θ	$t \cdot s^2 . m/m$	127.0	136.6 (143.6)	143.2 (155.5)	150.0 (167.3)	136.5	143.2	150.0
Main Cable	Distance of Cables	b	m	23.0	23.0	23.0	23.0	23.0	23.0	23.0
	Area	A_c	m^2	0.564	0.648	0.713	0.773	0.648	0.713	0.773
	Sag	f	m	100	100	100	100	87.273	80.408	74.815
	Horizontal tension	H_w	t	23125	27500	30625	33750	27500	30625	33750
Girder	Inertia (Vertical)	I_x	m^4	1.239	1.239	1.239	1.239	1.239	1.239	1.239
	Inertia (Lateral)	I_y	m^4	58.119	58.119	58.119	58.119	58.119	58.119	58.119
	Torsional Const.	J	m^4	3.30	3.30	3.30	3.30	3.30	3.30	3.30

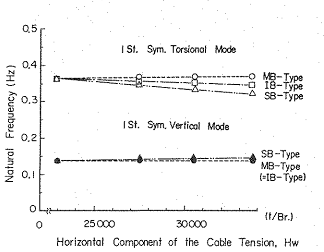

Fig. 14 Computed Natural Frequencies of Model Suspension Bridges (lst Symmetric Mode).

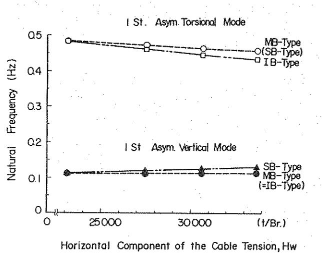

Fig. 15 Computed Natural Frequencies of Model Suspension Bridges (lst Asymmetric Mode).

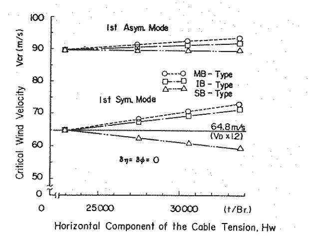

Fig. 16 Critical Wind Velocily of Coupled Flutter (Vcr= 0.8 x Computed Values).

inertia in MB-Type, and decreased by only about 4.5 % even in IB 3-Type with the polar moment of inertia increased by about 32 % compared with B-Type, but it is reduced by as much as about 12 % in SB-Type. These results are convincing, because the nondimensional natural circular frequency of torsional vibration ω_ϕ^* shown in Fig. 2 kept $P_{1,T}$ in the best range for MB and IB-Types, for which parameter P_2 changed almost constantly with the increase of $P_{1,T}$ and because ω_ϕ^* is reduced with the decrease of P_2 for SB-Type. On the other hand, the natural frequency of first asymmetric mode slightly reduced as polar moment of inertia increases, but considering that the vibration concerned is mainly of vortex excitation, the decrease to such an extent is not considered to result in a serious problem.

(3) Coupled flutter

In a streamlind box girder type suspension bridge, coupled flutter is the key phenomenon as mentioned before. In this connection, the structural characteristics of the respective types shown in Table 1 and the natural frequencies calculated in (2) were used to calculate the critical wind velocities of coupled fluter by Bleich's method[6]. In the calculation, the combinations of first symmetric and asymmetric modes were respectively considered, and the coupling coefficient between vertical and torsional mode shapes was assumed to be 1.0. Furthermore, since the structural damping little contributes to coupled flutter, it was disregarded. The values by multiplying the calculated value V_F by the correction coefficient of 0.8[19] were taken as critical wind velocities V_{cr} of the coupled flutter. The results are shown in Fig. 16. The wind velocity of 64.8 m/s shown in this figure was obtained by multiplying the design wind speed V_D based on the basic wind speed of V_{10}=37 m/s, by a safety factor of 1.2 and corresponds to the critical wind velocity of flutter for an angle of attack $\alpha=0°$.

Fig. 16 shows that the critical wind velocities for first symmetric mode are lower than those for first asymmetric mode, and hence the former dominates the design. For this coupled flutter of first symmetric mode, the critical wind velocity increased considerably with increasing horizontal component of the cable tension in MB and IB-Types. This was caused by the increase of the mass and polar moment of inertia, judging from the slight change of the torsional frequency and frequency ratio. On the other hand, in case of SB-Type, the critical wind velocity decreased with the decrease of sag-span ratio to be lower than $1.2\times V_D$. This might be due to the facts that, even though the polar moment of inertia slightly increased with the decreased of sag-span ratio, the mass increased slightly, and that the torsional frequency of first symmetric mode and frequency ratio remarkably decreased respectively.

(4) Vortex excitation

In order to analyze the time series response of vortex excitation, each model suspension bridge was firstly substituted by a lumped-mass system in three-dimension for obtaining eigenvalues. The vibration examied was the first symmetric torsional mode, and the computed result for B-Type is shown, as an example, in Fig. 17. In the figure, the parenthesized value is the frequency calculated by the linearized deflection theory and it can be seen that both the frequencies well coincide. With respect to the first symmetric torsional mode of vibration, the two-dimensional unsteady aerodynamic force obtained from the

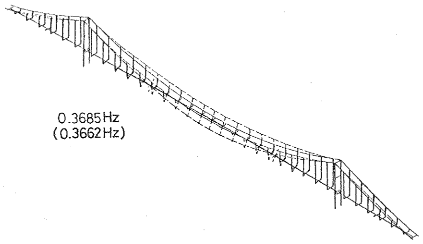

Fig. 17 Computed Frequency and Mode Shape of 1st Sym. Torsional Vibration (B-Type Bridge).

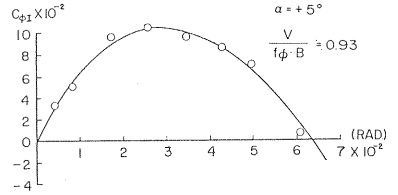

Fig. 18 Unsteady Aerodynamic Coefficients in Smooth Flow (MODEL Ⅲ).

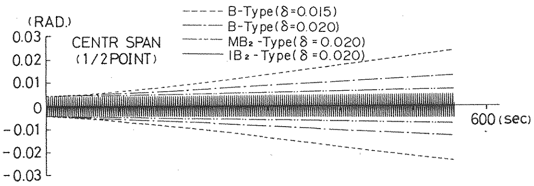

Fig. 19 Time Series Responses in Torsional Vortex Excitation (The unsteady aerodynamic force is applied to all spans).

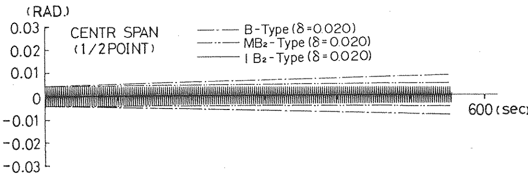

Fig. 20 Time Series Responses in Torsional Vortex Excitation (The unsteady aerodynamic force is applled to about 560 m of the center span).

sectional model tests shown in Fig. 8 (MODEL Ⅲ) was substitutionally used to numerically calculate the time series responses of the symmetric torsional vortex excitation of model suspension bridges using the strip theory[20]. The numerical calculation was made by using Newmark's β method ($\beta=1/6$), each minute time interval being 1/20 of the natural period. For the calculation, the unsteady aerodynamic coefficient was evaluated by the least square method as shown in Fig. 18, and the initial torsional displacement at the center of center span was set as 0.00436 rad. (0.25 deg.).

Fig. 19 shows the responses at the center of center span for the case that the unsteady aerodynamic force was applied to the stiffening girders of all spans. From this figure, it can be seen that the exciting force for torsional vortex excitation is very weak, and therefore that the torsional response is considerably decreased only with slight increase in the polar moment of inertia and structural damping in torsion. On the other hand, it is considered that the wind velocity to cause torsional vortex excitation acts rarely on all spans, considering the time of its development. Therefore, taking into accout the mode shape, the unsteady aerodynamic force was applied only to the about 560 m long stiffening girder of center span. The results are shown in Fig. 20, from which it can be seen that torsional vortex excitation kept still developing in B-Type, became almost steady in MB 2-type, and damped slowly in IB 2-Type.

5. CONCLUDING REMARKS

The effects of dead weight on the dynamic characteristics and the aerodynamic stability of the suspension bridges having box girder type stiffening frame (a side to center span ratio of 0.3) were investigated. Main conclusions obtained are summarized below.

(1) The natural frequencies of first symmetric and asymmetric mode of vertical vibration are little reduced even if the dead weight is increased to some extent. On the other hand, as for the torsional vibration, the effect on the natural frequency of first symmetric mode is larger than that on the frequency of first asymmetric mode. Furthermore, the ranges of nondimensional characteristic parameters not to reduce drastically the natural frequency of the first symmetric mode in torsion was presented under the condition that the polar moment of inertia increased to some extent.

(2) For the vortex excitation and coupled flutter in a streamlined box girder type suspension bridge, it could be indicated that the mass and polar moment of inertia are controling factors. The effect of polar

moment of inertia on stall flutter was also recognized but was not so remarkable.

(3) In the static design of a streamlined suspension bridge, the sag-span ratio may be slightly lessened to increase the rigidity of the entire suspension bridge system, but it is not preferable from aerodynamic viewpoint to make the sag-span ratio too small.

The relation between the dead weight and aerodynamic responses for the various types of cross sections must be examined for further study. Also, needless to say, the increase of dead weight will affect on the design of substructures and the dynamic behaviours induced by earthquakes. Although these effects must be made clear in the next step, the scope of this paper was confined to investigate the wind-resistant design problem.

5. ACKNOWLEDGEMENTS

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