MODAL DAMPING OF SUSPENDED CABLES

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ABSTRACT

Modal damping of flexural oscillation in suspended cable is investigated through free oscillation experiments with cable model and through finite element analyses. Relation between modal damping and dynamic characteristics of cable is discussed with parameters of sag-to-span ratio, span length, chord inclination, support flexibility and support damping. It is found that modal damping of cable is closely related to dynamic strain in normal mode and that internal damping of cable is a primary cause of modal damping of flexural oscillation. It is also found that damping at support contributes to modal damping directly and that the contribution of support damping is approximately proportional to square of modal support amplitude.

KEYWORDS: Cable, Experiment, Finite Element Analysis, Modal Damping.

1. INTRODUCTION

Cable has been widely used as structural member in civil engineering structures, such as suspension bridges, cable-stayed bridges, transmission lines, telecommunication lines, and so on. Especially in Japan, there is the big project; Honshu-Shikoku Bridge Project, of connecting two main islands by many over-sea bridges, most of which are cable-suspended bridges. Center span lengths of those suspension bridges are 770m, 876m, 940m, 990m, 1100m and 1990m. With the increase of span length in suspension bridge, cable becomes more and more important as structural member. As a matter of fact, it can be seen from Fig. 1 that weight proportion of cable to bridge deck increases almost linearly with span length. Fig. 1 indicates change of dead load ratio of cable to suspended structure with respect to center span length for Honshu-Shikoku Bridges and the Messina Straits Bridge in Italy. For the Akashi Straits Bridge center span of which will be 1990m, the weight of cable will be heavier and about 50% of the weight of suspended structure.

Fig. 2 is plots of maximum span length in cable-stayed bridge in Japan. As is shown in Fig. 2, many cable-stayed bridges have been constructed especially in this decade and the span length becomes longer and longer. This means cable becomes more and more important also in cable-stayed bridge.

Oscillations of cables, however, occur easily due to wind because of their light weight and high flexibility. Indeed remarkable oscillations, such as

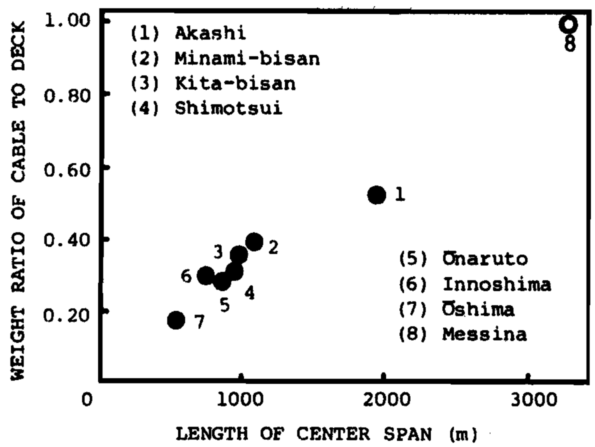

Fig. 1 Cable weight versus span length in suspension bridge

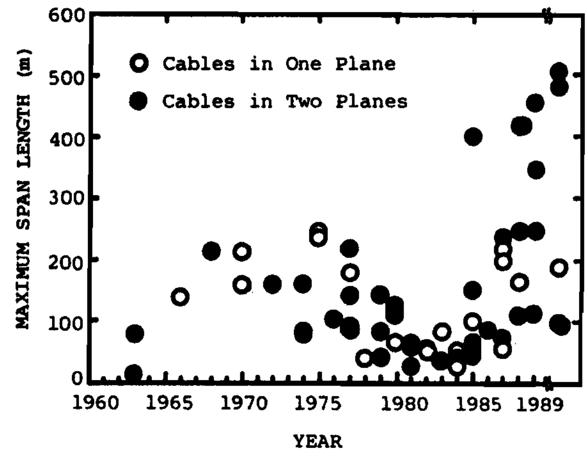

Fig. 2 Maximum span length of cable-stayed bridge in Japan

galloping and buffeting of cables in transmission lines, telecommunication lines, and cable-stayed bridges, have been reported frequently (see, for example, Rawlins [1981]; Fujino et al. [1988]; Hikami and Shiraishi [1988]) and recently the relatively new problem of rain and wind-induced vibration of cable becomes a serious engineering issue in cable-stayed bridges (Hikami and Shiraishi [1988]). Occurrence of wind-induced oscillation is much dependent on modal damping and the damping mechanism of cable is very important to consider suppression of such kind of oscillation.

Several studies have been made on damping characteristics of cables and wire ropes. Most of them deal either the first flexural modal damping of taut cable or with hysteresis damping of wire rope during axial oscillation (Hara and Ueda [1966]; Nishimura et al. [1977]; Tsuji and Kanou [1980]; Tanaka et al. [1985]; Kanou and Tsumura [1987]). This means that researches have been conducted mainly on the material damping of ropes, while there are very few investigations on the modal damping of flexural oscillation in suspended cables (Ramberg and Griffin [1977]; Yamaguchi and Fujino [1987,1988]; Yamaguchi [1988]).

The primary objective of the present paper is to investigate modal damping characteristics of flexural oscillation in suspended cables through model experiments and finite element analyses. The sag-to-span ratio is chosen as a primary parameter in the testing and it is studied how the modal damping changes as the sag ratio changes. In addition, effects of initial tension, chord inclination, support flexibility and support damping on modal damping of cable are also discussed and the damping mechanism of cable is clarified.

2. OSCILLATION TEST WITH MODEL CABLE

Model cable employed in the experiment is 7-wire strand rope to which lead weights (15.0g/weight) are attached at interval of about 9.5cm distances in order to adjust weight of cable model. The tensile rigidity, tensile strength and mass per unit length of cable are 2.40×10^2[kN], 2.74[kN] and 0.17[kg/m], respectively. The details of cable model are shown in Fig. 3.

As is shown in Fig. 4, the model cable was wound with several turns around a horizontal bar steel fixed to a thick steel plate which was connected rigidly to a rigid support, and then mounted in the support through turnbuckle. Sag of cable

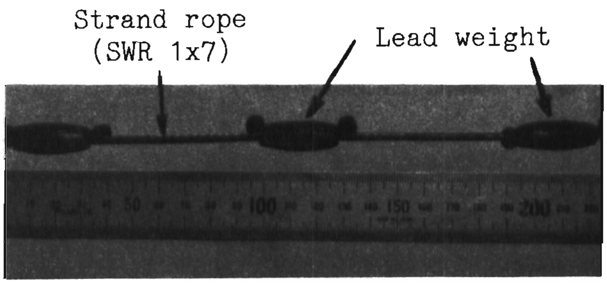

Fig. 3 Details of model cable with lead weight

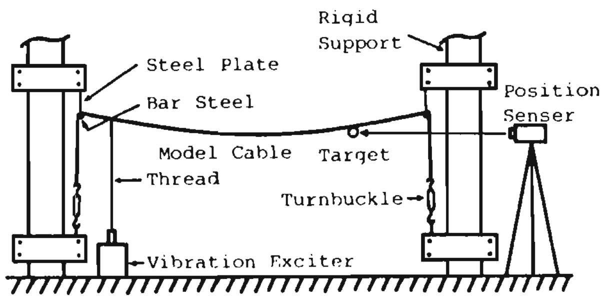

Fig. 4 Schematic diagram of experimental set-up

was adjusted by the turnbuckle. The test cable set up with required sag-to-span ratio was forced to oscillate at each natural frequency by using vibration exciter which was connected to one point of cable through a thread. The thread was cut after stationary oscillation was attained, and the subsequent decay of free oscillation was recorded and analyzed to obtain natural frequency and modal damping. The excitation point was changed such that the mode concerned was purely excited. The dynamic displacement was measured by means of an electro-optical displacement follower (position sensor), a target of which was attached to the cable at the point of the largest amplitude of mode shape.

The span length and chord inclination were chosen as 7.3m and 0 degree, respectively. The sag-to-span ratio was changed from 0.005 to 0.1 considering sag ratios of real cable structures.

3. FINITE ELEMENT ANALYSIS OF CABLE OSCILLATION

Finite element analyses of free oscillation of cables were made in order to calculate natural frequencies, normal modes and additional dynamic strains. The 3 nodes quadratic element with shape function of quadratic polynomial was used and the matrices, such as mass and elastogeometric matrices, obtained by Henghold and Russell [1976] were applied. The static configuration due to dead load was analyzed first, and next eigenvalue problem was solved for small oscillation about the nonlinear equilibrium position by evaluating the tangential stiffness matrix. Using obtained mode vectors which are normalized relative to the maximum displacement value, additional dynamic strain at the internal node of each element is then calculated. Since each internal node has different value of dynamic strain, the root mean square of dynamic strains is taken as a representative value for each normal mode. Details of analyses are referred to Yamaguchi and Fujino [1987].

4. CHARACTERISTICS OF MODAL DAMPING

Fig. 5 shows the relation between natural frequency and sag-to-span ratio. Experimentally measured values are plotted with theoretically estimated curves for each natural mode. The distinct feature in this figure is in-plane symmetric mode. That is, there exists so-called modal transition (Yamaguchi and Ito [1979]) in certain region of sag ratio. In this modal transition region, the mode shape of symmetric mode changes into the one order higher symmetric mode with the increase of natural frequency, while natural frequencies of other modes decrease monotonically. Therefore, there exists modal crossover point at which natural

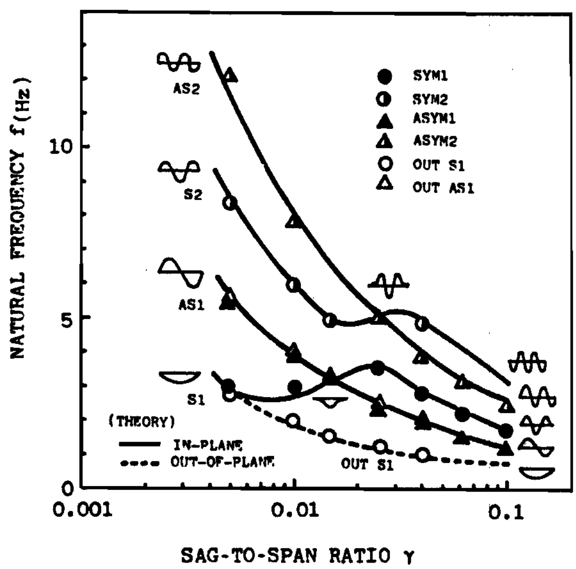

Fig. 5 Natural frequency versus sag-to-span ratio

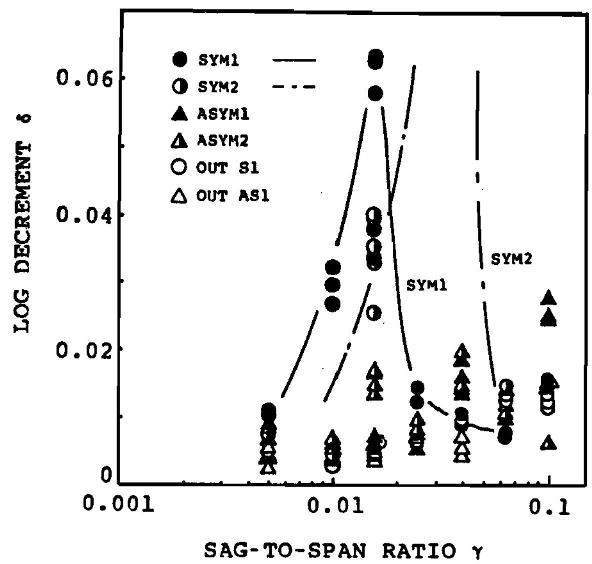

Fig. 6 Modal damping versus sag-to-span ratio

frequency of symmetric mode coincides with that of asymmetric mode.

The experimentally measured values of corresponding modal damping represented by logarithmic decrement are shown in Fig. 6. Modal damping of cable is dependent on amplitude as has been reported by Yamaguchi and Fujino [1987], so that the damping was measured at the peak amplitude of mode shape nearly equal to 0.24% of span length. The logarithmic decrements shown in Fig. 6 were evaluated at the reference amplitude. It can be seen in Fig.6 that the damping of in-plane symmetric mode is larger than other modal damping in the modal transition region,

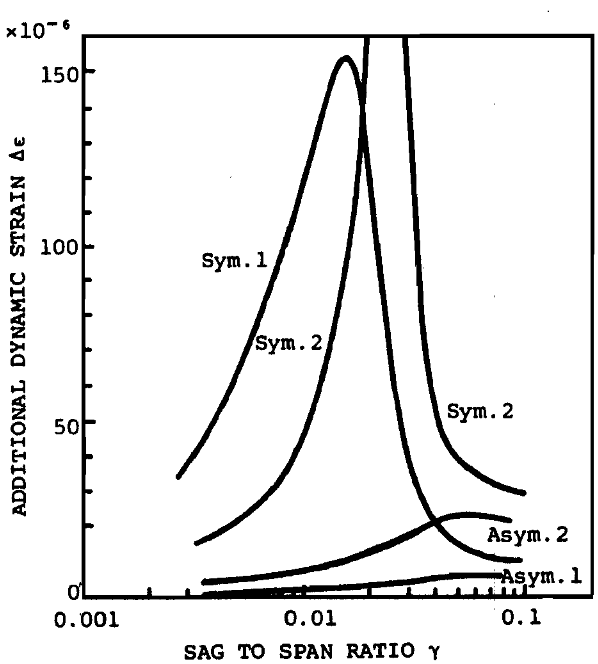

Fig. 7 Additional dynamic strain versus sag-to-span ratio

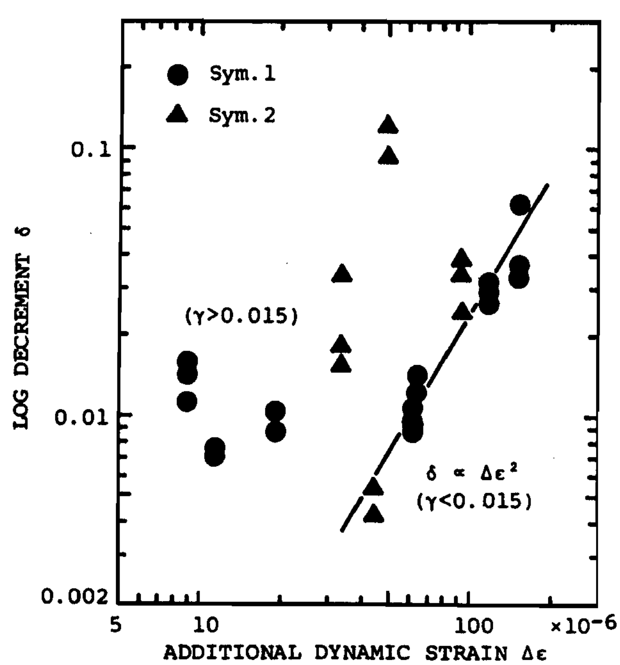

Fig. 8 Modal damping versus additional dynamic strain

especially for the sag-to-span ratio around the modal crossover point. On the other hand, the damping for in-plane asymmetric modes and for out-of-plane modes is small and slightly increasing value over a wide range of sag-to-span ratio. It is concluded here that modal damping of cable for in-plane symmetric mode can be larger than modal damping for in-plane asymmetric and out-of-plane modes depending on sag ratio of cable.

The dynamic strain of cable during free oscillation was calculated for each normal mode in order to investigate the relation between modal damping and hysteresis energy, because the internal damping due to hysteresis energy is expected to be one primary source of cable damping. Fig. 7 is a plot of calculated dynamic strain versus sag ratio. As can be seen from Fig. 7, the change of dynamic strain with respect to sag ratio is quite similar to that of modal damping in Fig. 6. That is, the additional dynamic strain of symmetric mode takes large value in the modal transition region and has a maximum at the modal crossover point, while the dynamic strain of in-plane asymmetric mode is smaller in comparison with the symmetric mode and the dynamic strain of out-of-plane mode equals to zero in the linear theory.

The relation between modal damping and dynamic strain is shown more directly for in-plane symmetric mode in Fig. 8 where the abscissa is the calculated dynamic strain and the ordinate is the measured log decrement both in log scales. The data points plotted lie almost in a straight line of slope 2 in case of sag ratios less than the modal crossover point ($\gamma < 0.015$). This means that the modal damping is in proportion to the square of dynamic strain, and that internal damping is primary cause of modal damping of cable.

Correspondence of modal damping to square of dynamic strain is poor for large sag ratios in Fig. 8 but this may be partly due to accuracy in the evaluation of dynamic strain. If geometrical nonlinear theory (Yamaguchi and Fujino [1987]) is applied , the dynamic strain for large sag ratio is calculated larger than that of linear theory (Fig. 9), and the correspondence of modal damping to square of dynamic strain for large sag ratio is improved as is shown in Fig. 10. The analysis based on the nonlinear evaluation of dynamic strain,

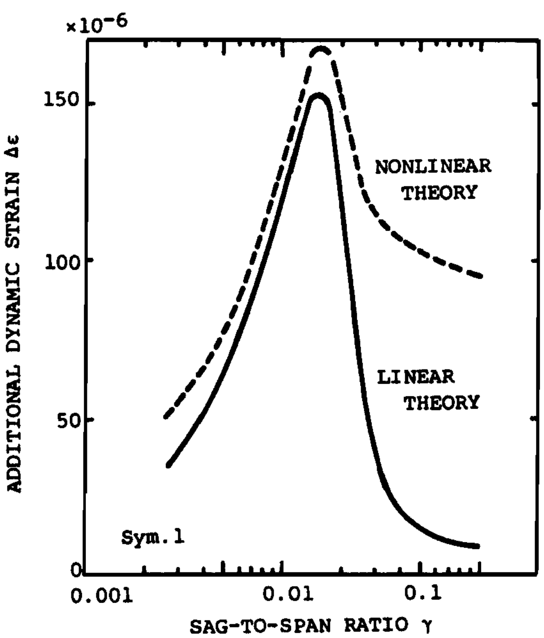

Fig. 9 Dynamic strain estimated by nonlinear theory

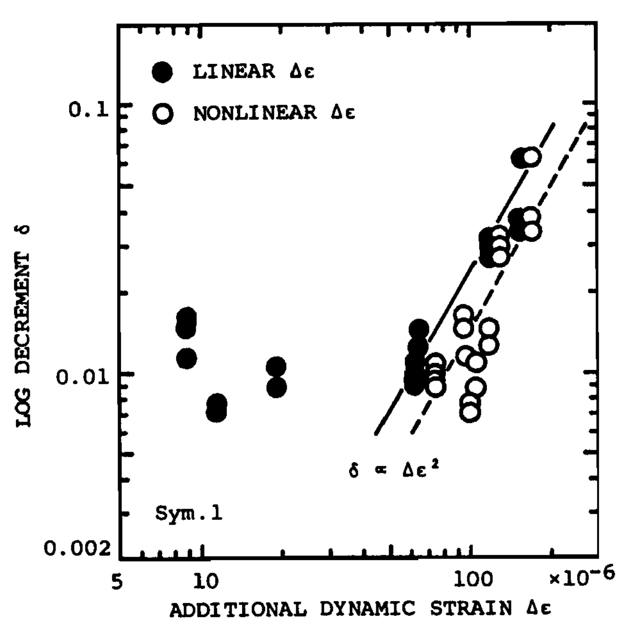

Fig. 10 Modal damping versus nonlinear dynamic strain

however, is difficult to check its accuracy and is not so reliable because nonlinear equation was used only for the evaluation of dynamic strain with linear solution of normal mode vector. The additional dynamic strain calculated by linear theory, therefore, will be only discussed in the following sections.

5. EFFECTS OF SPAN LENGTH ON DAMPING

Modal damping of shorter spanned cable was also measured and the effect of span length on modal damping is considered. Fig. 11 is again the relation between modal damping and dynamic strain with the new data of short cable of 2.05m span. Only data of the in-plane first symmetric mode are shown in comparison. It can be seen from Fig. 11 that the data points of short cable also lie in a straight line of slope 2. The straight line, however, is different for different span length in spite of same cable. This is supposed to be caused by the effect of initial tension of cable on internal damping.

The effect of initial tension on the first modal damping of taut cable has been reported by Hara and Ueda [1966], Nishimura et al. [1977] and Tanaka et al. [1985]. Those experimental data are arranged in Fig. 12 with the abscissa of initial tension nondimensionalized by tensile strength. In Fig. 12, the log decrement is greatly changed up to the order of 10% initial tension ratio and is larger for lower initial tension, while the log decrement takes almost constant value when the initial tension is introduced to a certain degree. This means that the friction between each wire of cable is changed by the initial tension. It should be mentioned that this characteristics of initial-tension effect is independent on what the cable is; strand wire rope, or parallel wire strand, or locked coil rope, or parallel wire cable.

Fig. 13 shows same plots of the present experimental results but on a log-log graph paper for the asymmetric and out-of-plane modes. Since modal damping of asymmetric and out-of-plane modes is not affected very much by the dynamic

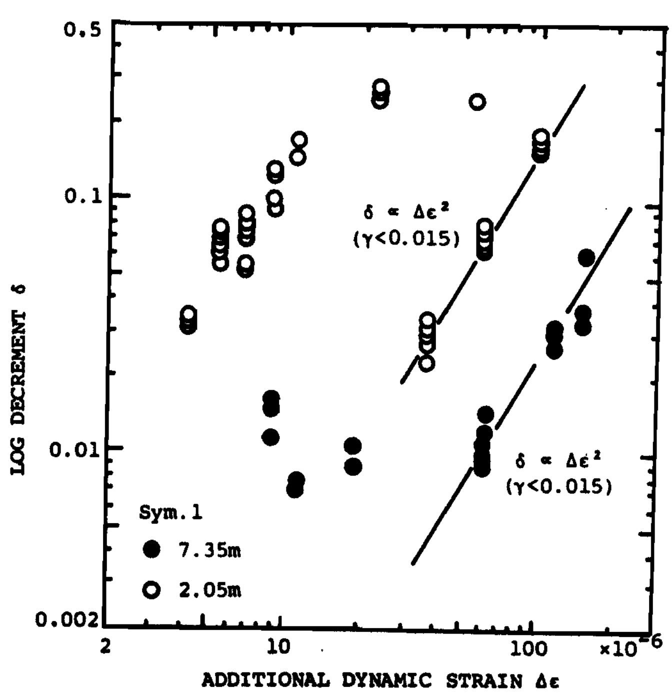

Fig. 11 Effect of span length on damping-strain relation

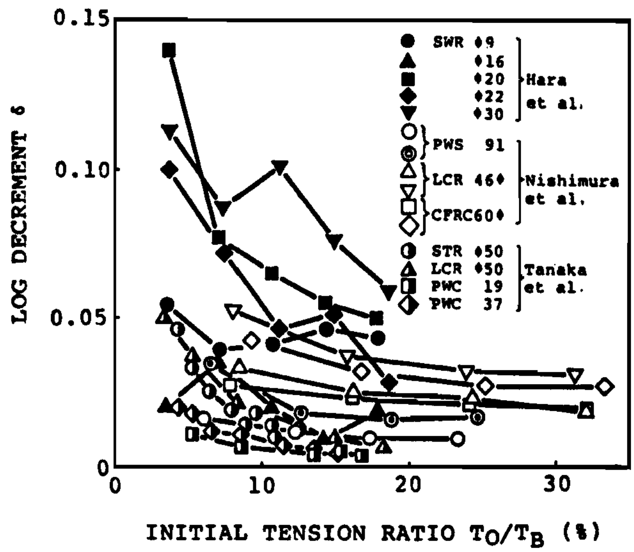

Fig. 12 Log decrement versus initial tension for taut cable

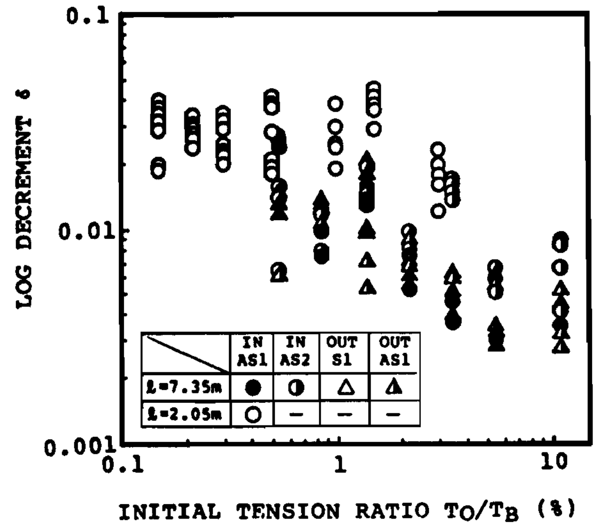

Fig. 13 Modal damping versus initial tension

strain, effects of initial tension can be investigated directly from Fig. 13. As can be seen from Fig. 13, the modal damping becomes larger for shorter cable because of low initial tension. Consequently, the difference in the first symmetric modal damping for different span length, shown in Fig. 11, can be due to this fact.

6. MODAL DAMPING OF INCLINED CABLE

Since cable in real structure such as cable-stayed bridge is sometimes supported at different level, the damping of inclined cable is also investigated. Fig. 14 is the plots of natural frequency versus sag ratio for 30 degrees inclined cable. It can be seen from Fig. 14 that the modal transition is different from that of horizontally supported cable in Fig. 5. That is, in case of inclined cable, the in-plane symmetric mode changes into the higher asymmetric mode and the asymmetric mode into the higher symmetric mode when the sag ratio

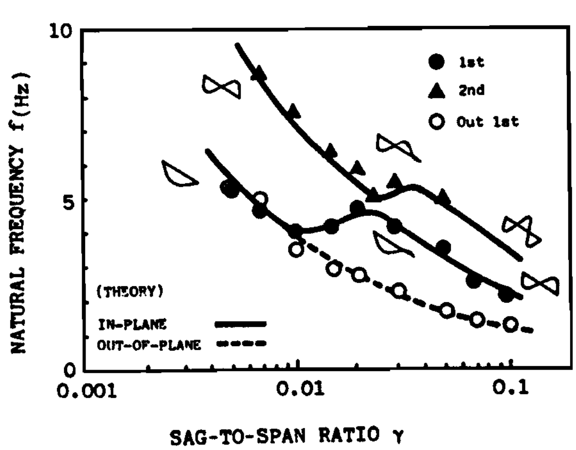

Fig. 14 Natural frequency versus sag ratio in inclined cable

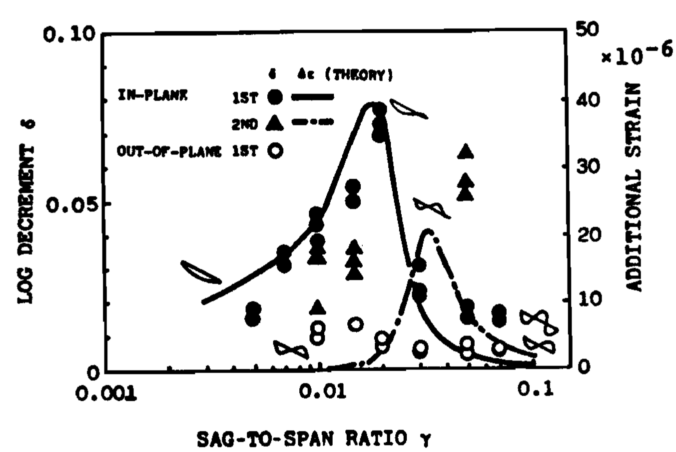

Fig. 15 Comparison of modal damping with dynamic strain in inclined cable

becomes larger (Yamaguchi and Ito [1979]). The comparison between corresponding modal damping and dynamic strain is presented in Fig. 15. The modal damping is again large in the modal transition region but the tendency is somewhat different from that for the horizontally supported cable. Even in the modal transition region, the modal damping decreases rapidly when the normal mode approaches the asymmetric mode, while the damping for pseudo-symmetric mode are still large. Changes of modal damping and dynamic strain with respect to sag ratio, however, correspond to each other very well also for the inclined cable, and the modal damping of cable can be again explained by internal damping of cable.

7. EFFECTS OF SUPPORT FLEXIBILITY ON MODAL DAMPING

Modal damping of rigidly supported cable was investigated in the previous sections and effects of support flexibility on modal damping are discussed next. Cable is always supported elastically in a sense in real structures and the condition of support seems to be very important in estimating wind-induced oscillation. An example can be seen in the wind tunnel study by Fujino et al. [1984] on galloping of telecommunication cable that the mode during galloping was different when the different flexibility of end support was used.

The thin steel plate of 2.5mm thickness was used at support in the experimental set-up, shown in Fig. 4, in order to realize the elastic support condition. The dynamic characteristics of support were measured directly by performing static and dynamic tests before suspending cable model. The equivalent spring constant in horizontal direction at support is 6.0kN/m and the first modal mass of cantilever plate is 0.55kg.

Fig. 16 shows theoretically estimated natural frequencies for elastic support and fixed support. There exists modal transition regardless of support condition but the transition region shifts to larger sag ratio as the support becomes flexible. The natural frequency of symmetric mode for flexible support, therefore, decreases for sag ratios in the modal transition region. As for cable

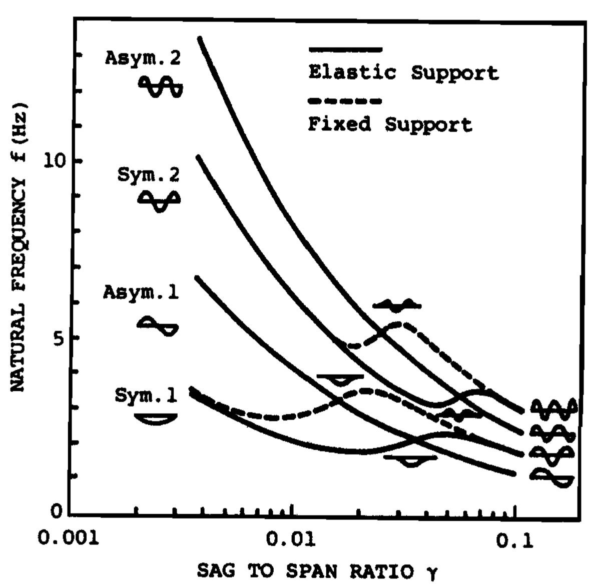

Fig. 16 Natural frequencies of elastically supported cable

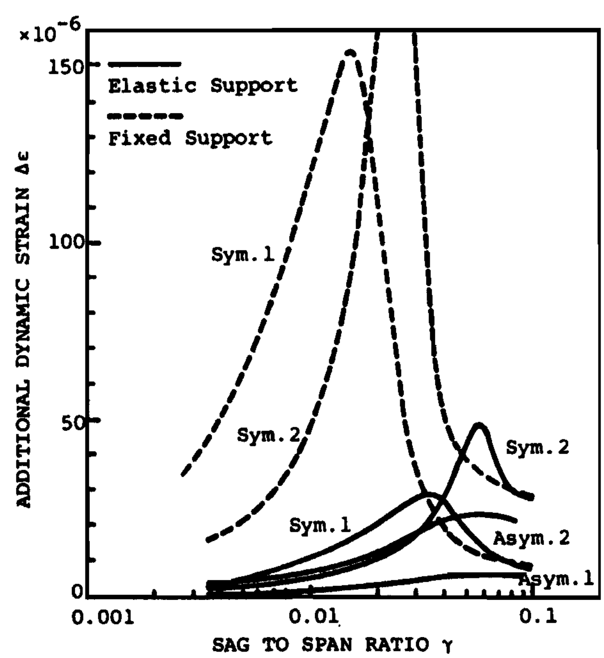

Fig. 17 Dynamic strains of elastically supported cable

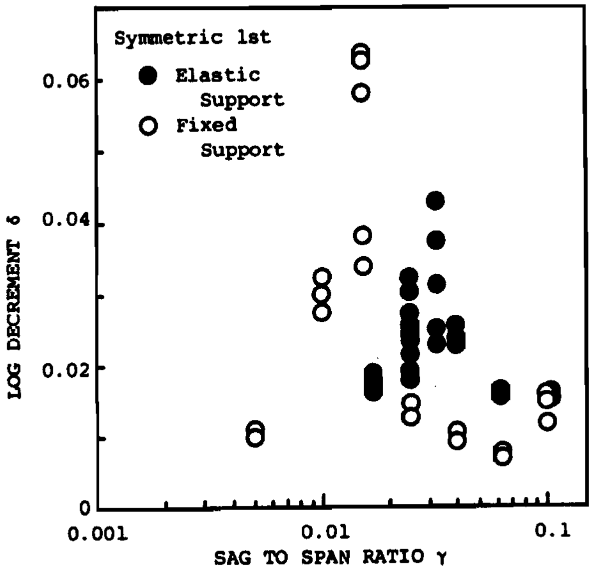

Fig. 18 Comparison of the first symmetric modal damping

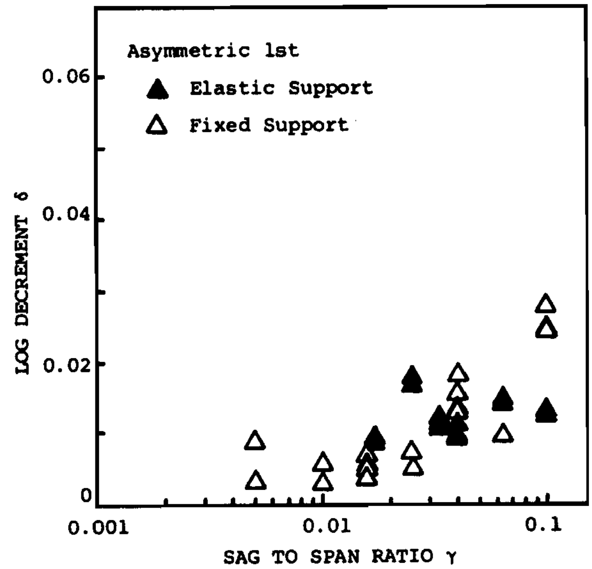

Fig. 19 Comparison of the first asymmetric modal damping

with sag ratio outside of the modal transition region, there is not so much difference in the natural frequency of symmetric mode. It should be mentioned that the natural frequency of asymmetric mode is not influenced by the support condition.

The corresponding dynamic strain of symmetric mode takes large value in the modal transition region even for elastic support as is shown in Fig. 17. The maximum dynamic strain of flexibly supported cable, however, becomes much smaller than that of rigidly supported cable, while dynamic strains of asymmetric modes for two support conditions lie on the same curve.

Corresponding to this tendency in dynamic strain, modal damping of the first symmetric mode is much affected by support flexibility. Fig. 18 shows the comparison of the first symmetric modal damping versus sag ratio for two support conditions. As can be seen from Fig. 18, the mutual relation of modal damping in magnitude for different support condition depends on the sag ratio. That is, the damping of flexibly supported cable is smaller for small sag ratio but is larger for large sag ratio, and maximum damping value becomes smaller for flexible support. On the contrary, modal damping of asymmetric mode is not significantly influenced by support flexibility (Fig. 19). This is because the asymmetric mode of elastically supported cable does not include support movement (Yamaguchi and Fujino [1988]).

Fig. 20 is again the relation between experimentally measured modal damping and theoretically calculated dynamic strain. In Fig. 20, the data points of symmetric mode plotted for elastic support also lie roughly in a straight line of slope 2. This means that the modal damping is in proportion to square of dynamic strain and that the internal damping is one of the primary causes of modal damping even for flexibly supported cable. The straight line of slope 2 for each support condition, however, differs from each other, nevertheless the same cable was used in all the cases in the experiment; the straight line shifts to the left for flexible support. This result suggests existence of another cause of modal damping which could be the result of energy loss at support. That is, the damping at support might have direct effects upon the total damping of cable. This effect of energy dissipation from flexible support will be discussed next.

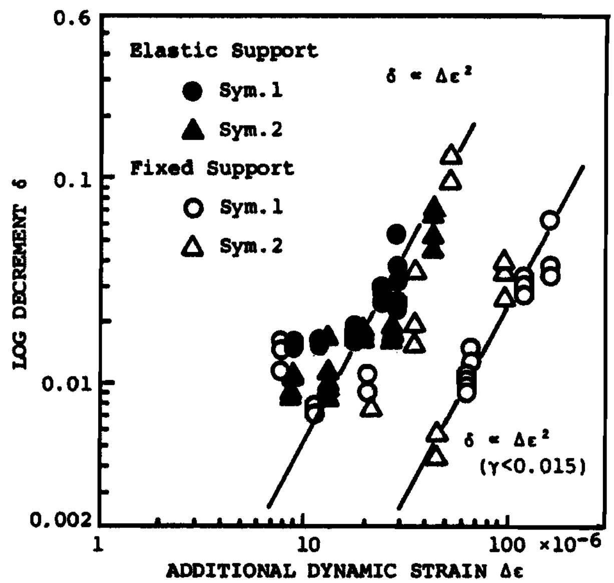

Fig. 20 Effect of support flexibility on damping-strain relation

8. EFFECTS OF SUPPORT DAMPING ON MODAL DAMPING

A damper was set at elastic support and modal damping of cable with support damping was measured in the same experimental procedure as previous sections. Details of damper are shown in Fig. 21. Damping value at support can be changed by changing the depth of water in the tank. Two values of water depth, 9cm and 18cm, were chosen in the experiment and damping of support itself was measured experimentally. The support damping represented by log decrement is shown in Fig. 22. Damping value of support is about 0.05 for low support-damping (9cm) and 0.15 for high support-damping (18cm) in case of small amplitude of 0.5mm.

Fig. 23 shows natural frequencies of the first symmetric mode with those of asymmetric mode which are plotted to indicate the modal crossover point. There is no significant difference in natural frequency between each support-damping

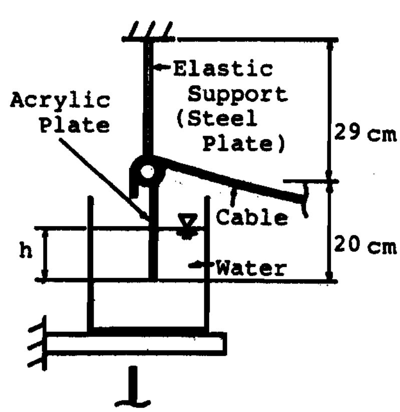

Fig. 21 Details of damper at support

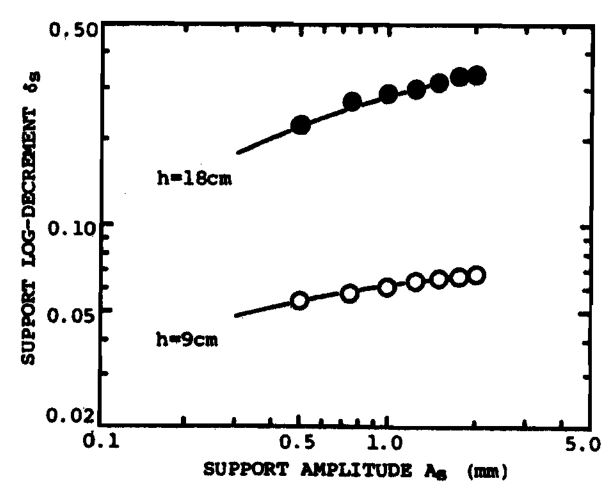

Fig. 22 Support damping versus support amplitude

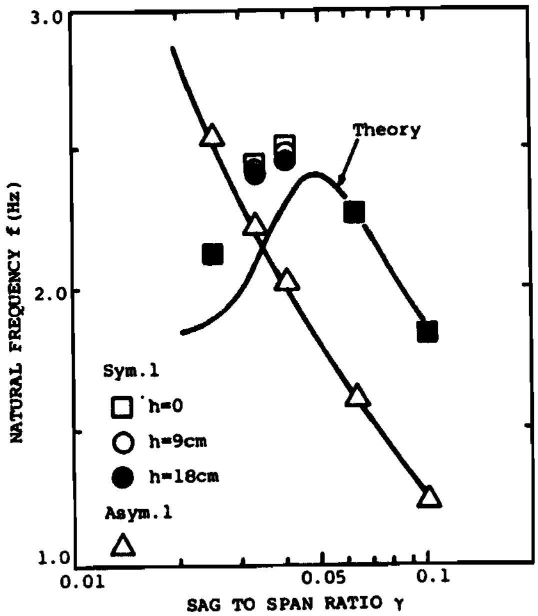

Fig. 23 Natural frequencies of cable with support damping

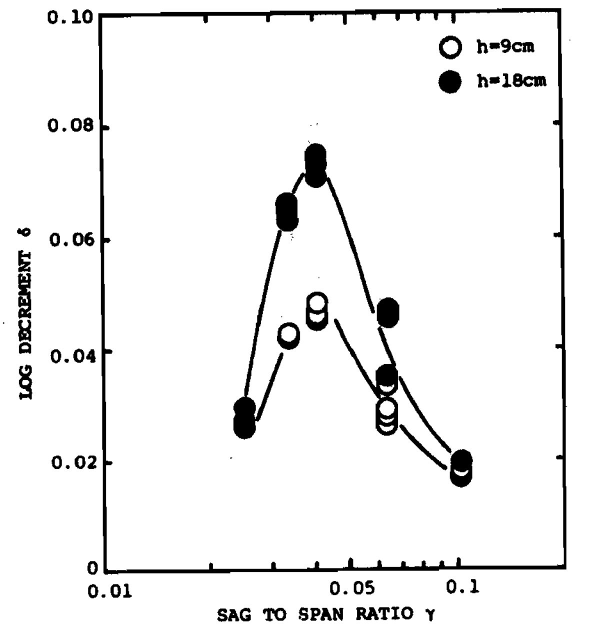

Fig. 24 Modal damping versus sag ratio for cable with support damping

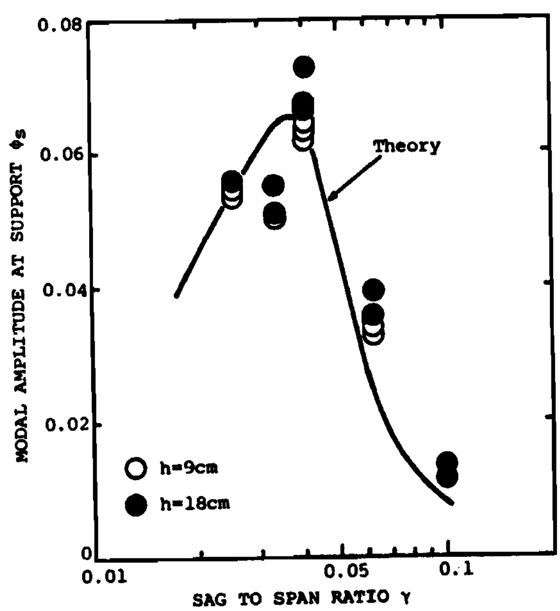

Fig. 25 Modal amplitude at support versus sag-to-span ratio

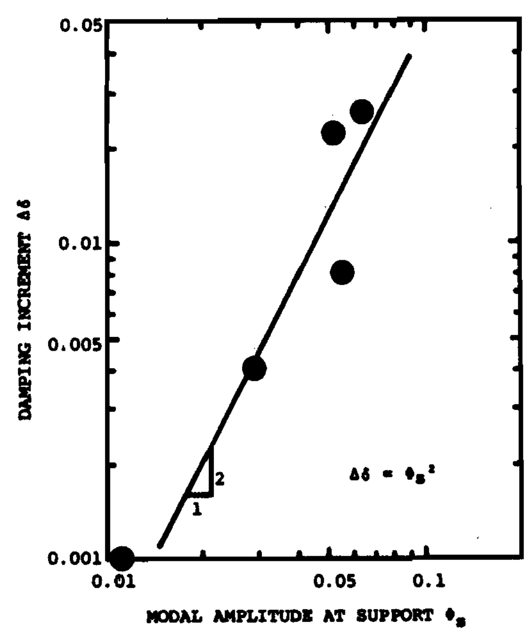

Fig. 26 Modal damping increment versus modal support amplitude

condition. This means that the damping at support is sufficiently low.

The corresponding modal damping of the first symmetric mode is large in modal transition region as is shown in Fig. 24. Modal damping of cable with high support-damping (18cm) is larger than that with low support-damping, but the increment of modal damping depends on sag ratio. That is, the modal damping increases significantly at the modal crossover point where the modal damping takes maximum value, while there is small difference for sag ratio outside of modal transition region.

This may be due to different amount of support movement for each sag ratio. The support amplitude was, therefore, checked experimentally and theoretically. Fig. 25 is the result. The change of support amplitude with respect to sag ratio is quite similar to the change of damping increment caused by high damping at support. Fig. 26 shows the relation between damping increment and support amplitude in log-log graph paper. The damping increment was defined as difference between modal damping for h=18cm and h=9cm, and was calculated with experimental values shown in Fig. 24. As can be seen in Fig. 26, the data points plotted lie roughly in a straight line of slope 2. From this experimental fact, it can be estimated that the contribution of support damping is approximately proportional to square of modal support-amplitude and this has been estimated theoretically by Yamaguchi [1988].

9. CONCLUSIONS

Modal damping of flexural oscillation in suspended cable was discussed in relation to dynamic characteristics of cable. Major conclusions obtained through the present investigation are summarized as follows.

(1) Modal damping of in-plane symmetric mode is larger than other modal damping in the modal transition region.

(2) Modal damping is closely related to additional dynamic strain and one of primary causes of damping is internal damping of cable.

(3) Modal damping is larger for lower initial tension but almost independent on initial tension when the initial tension exceeds a certain level.

(4) For inclined cable, characteristics of damping are somewhat different from those for horizontally supported cable.

(5) Flexibility of support has significant effects only upon modal damping of symmetric mode in the region of modal transition.

(6) Contribution of support damping to modal damping of suspended cable is approximately proportional to square of modal support-amplitude.

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