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Dynamic behavior of cable-stayed bridge with damping

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Abstract

Cable-stayed bridges are flexible structural systems. These flexible systems are susceptible to the dynamic effects of wind and earthquake loads. The investigation of dynamic response for long-span Cable-stayed bridges largely depends on a detailed understanding of their dynamic characteristics. With the increasing central span of modern cable-stayed bridges, the trend of the bridge to use more shallow and slender girders to meet the requirements of aerodynamics. In this case, bridge safety (strength, stiffness and stability) under severe loadings and environmental dynamic loadings such as winds and earthquakes presents increasingly important concerns in both design and construction. Damping is a solution that can be used in the long-span Cable-stayed bridges efficiently and economically to control the dynamic loadings. In this study, the dynamic analyses with damping and without damping of a number of long Cable-stayed bridges are performed. For analysis, computer software SAP2000 v 8.1.2 was used. The analysis was performed with the variation of the mass and effective stiffness of the damper, which indicates that effective stiffness of damper is important parameter and mass of damper is not significant. From the analysis, it was found that with the application of damper in the Cable-stayed bridges, response due to wind loads and earthquake loads and the natural period of the bridge can be reduced and controlled effectively and efficiently. The damping parameters that found from the analysis can be used as a guideline for using damper in the Cable-stayed bridges to get optimum results and which is also economically viable.

Keywords: cable-stayed bridge, damping, natural period, effective stiffness

1. Introduction

The problems with long span bridges such as cable stayed bridges, suspension bridges etc are that they are very flexible in nature and their dynamic properties are very difficult to evaluate. Such long span bridges need to be designed for various dynamic loads such as wind loads and earthquake loads. These loads are dynamic and their pattern cannot be

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accurately anticipated. To design for such loads the dynamic behavior of the structure must be controlled. One way to do this is to control the natural frequencies of the structure. The dynamic behavior of a cable-stayed bridge can be controlled either by increasing stiffness of the structures or using damping in the bridges. Damping is more economical solution than increasing stiffness.

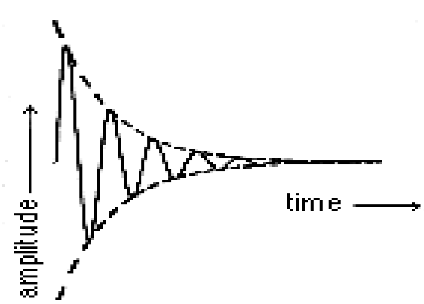
This study concentrates on the dynamic analysis of cable-stayed bridges and attempts to provide the designers a set of guidelines or some other forms. From that they can get the indication of the optimum values of various parameters of a damper and their variations with different dynamic analyses like modal analysis, time history analysis and response spectrum analysis.

2. Dynamics of structure

Dynamic analysis of three-dimensional structural systems is a direct extension of static analysis. The elastic stiffness matrices are the same for both dynamic and static analysis. It is only necessary to lump the mass of the structure at the joints. The addition of inertia forces and energy dissipation forces will satisfy dynamic equilibrium. The dynamic solution for steady state harmonic loading, with and without damping, involves the same numerical effort as a static solution. Classically, there are many different mathematical methods to solve the dynamic equilibrium equations. The majority of both linear and non-linear systems can be solved with one numerical method. Energy is fundamental in dynamic analysis. At any point in time, the external work supplied to the system must be equal to the sum of the kinetic and strain energy plus the energy dissipated in the system. With respect to earthquake resistant design, effort should be given to minimize the mechanical energy in the structure. It is apparent that a rigid structure will have only kinetic energy and zero strain energy. On the other hand, a completely base isolated structure will have zero kinetic energy and zero strain energy. A structure cannot fail if it has zero strain energy.

3. Damping

In designing a cable-stayed bridge, attention should be given to the possibility of generating any of the natural periods of vibration. Due to the relatively great flexibility of cable-stayed bridges, they are more susceptible to undesirable vibrations than conventional beam structures. Therefore, because of these vibrations of cable-stayed bridges, the characteristic of damping is of great importance.



Dashed line indicates exponential decay of the amplitude.

Fig .1. Exponential damping of a sine wave.

‘Damping’ is a term broadly used to denote either the dissipation of energy in, and the consequent decay of, oscillation of all types, or the extent of the dissipation and decay. Damping may be defined as the inherent force that causes the gradual dying out of mechanically excited natural vibrations within a structural member and reduces the efficiency of transfer of dynamic mechanical forces through a structure.

4. Application of damper in structures

Dampers are applicable to both fixed and base isolated structures, including buildings, bridges, and lifeline equipment.

Dampers are very effective in a large building or bridge to be more survivable during an earthquake. With most structures, a relatively small amount of damping provides a large reduction in stress and deflection by dissipating energy from the structure. Like an automobile suspension, in a building where the spring forces are supplied by the building columns or base isolators which both support the building and deflect under load. It requires only a small amount of viscous damping force to reduce building deflection by a factor of two or three while simultaneously reducing overall column stresses

Dampers reduce building deflection and stress at the same time. If dampers are used to limit the deflection, it won't increase the load into the building columns. Damping reduces stress and deflection because the force from the damping is completely out of phase with stresses due to flexing of the columns. If a Damper is added to the building, damping force will drop to zero at this point of maximum deflection. This is because the damper stroking velocity goes to zero as the column reverses direction. As the building flexes back in the opposite direction, maximum damper force occurs at maximum velocity, which occurs when the column flexes through its normal, upright position. This is also the point where column stresses are at a minimum.

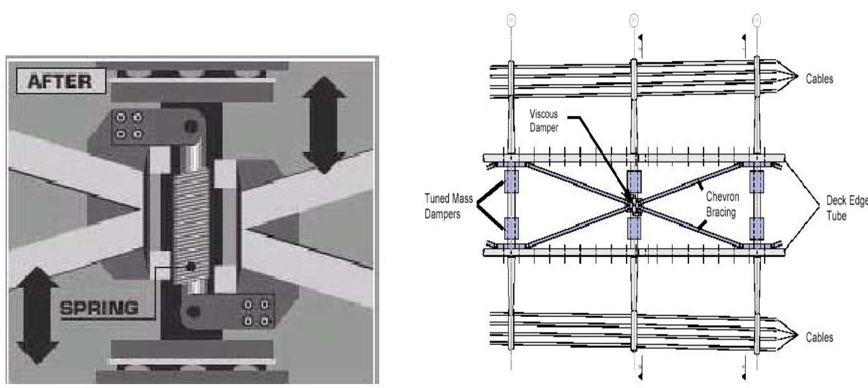


Fig. 2. Viscous and tuned mass dampers in The Millennium Bridge

A typical building normally has internal structural damping of 1 to 3 percent of critical. Optimal performance of a building with damping is achieved with damping in the range of 20 to 25 percent of critical. Experiments with building models have indicated additional improvements with damping increased to as much as 50 percent of critical, but eventually the gain goes past the point of diminishing returns from the point of damper cost.

Dampers are very effective in reducing building deflections under wind loadings without changing the stiffness of the building. In the case of tall buildings, wind motion can cause complaints of motion sickness and general discomfort from the occupants on higher floors. Dampers can reduce wind deflection by a factor of 2 or 3, greatly reducing occupant discomfort without creating localized stiff sections. New buildings designed with Dampers for mitigation of wind motion can be built with reduced lateral stiffness detailing, resulting in a less costly overall structure.

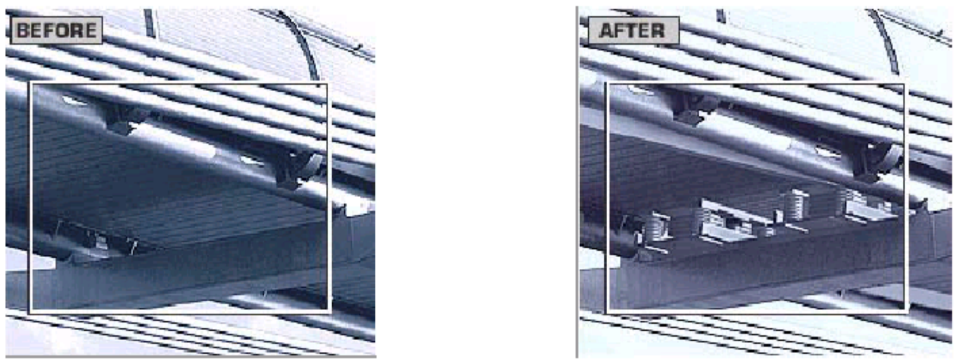


Fig. 3. Addition of tuned mass dampers in The Millennium Bridge

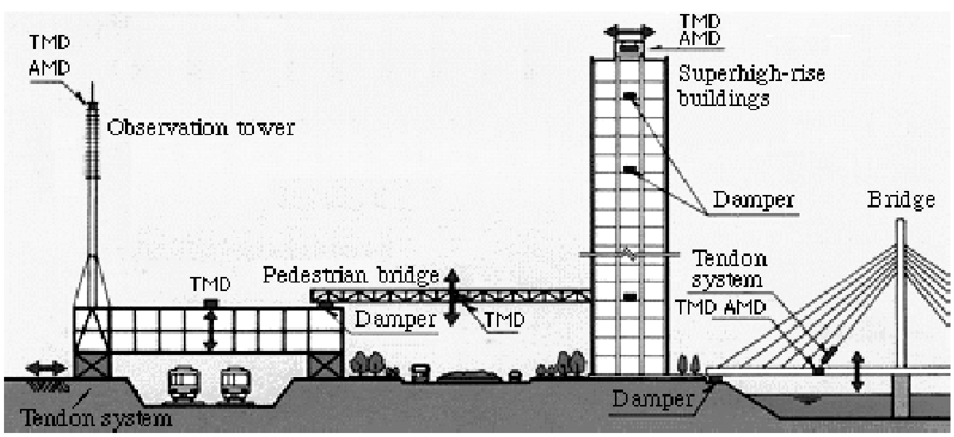


Fig. 4. A structural control device for earthquake-threatened structures

5. Methodology

In this study computer models of Cable-Stayed Bridges (Four types: Fan Type, Star Type, Radial Type and Harp Type) are developed using a specialized software (Sap2000 version 8.1.2) and a number of analyze are performed for each model with and without damping. First analysis performed is the modal analysis with damping from which optimal damping properties (mass of damper and effective stiffness of damper) are selected and these values of damping properties are used for dynamic analysis of modeled Cable-Stayed Bridges with damping. Then analyze are performed for earthquake loads (Response spectrum analysis) and wind loads (Time history analysis) for each model both without damping and with damping to study the dynamic response of cable-stayed bridge. Response-spectrum analysis is a statistical type of analysis for the determination of the likely response of a structure to seismic loading. Time-history analysis is a step-by-step analysis of the dynamical response of a structure to a specified loading that may vary with time.

For this purpose, a finite element modeling of Cable-Stayed Bridge is developed by using finite element package, SAP2000 version 8.1.2.The task of structure modeling is arguably the most difficult one facing the structural analyst, requiring critical judgment and a sound knowledge of the structural behavior of the bridge components and assemblies. Also the resulting data from the analysis must be interpreted and appraised with the discernment for use with the real structure, in order to serve as a reasonable basis for making design decisions.

- Modal analysis
- Response spectrum analysis
- Time history analysis

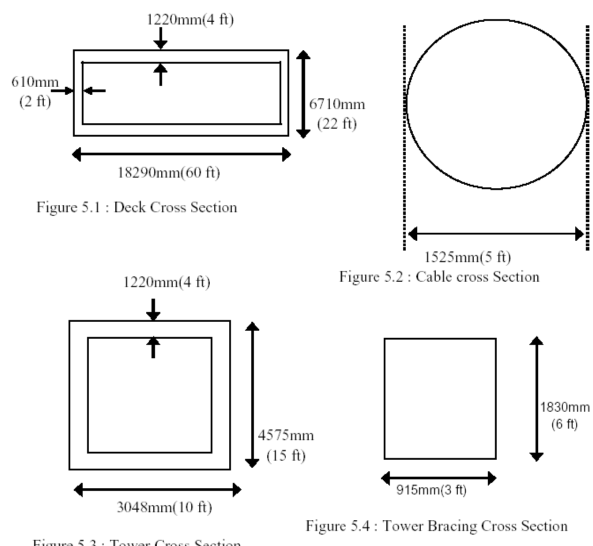


Fig. 5. Cross Sections of the modeled cable-stayed bridge

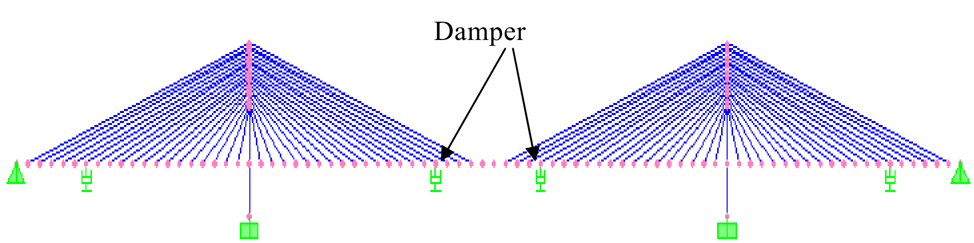


Fig. 6. Modeled cable-stayed bridge with damper

6. Analysis and results

In this study a number of Cable-stayed bridges with a constant central span 625m (2050 ft) and side span 305m(500 ft) and with different values of various parameters of damper were analyzed. For performing the analysis finite element method was used. Computer software SAP2000 was used for this modal analysis. The first 12 modes are considered in this study and mode 1 is used for analysis.

First modal analysis was performed with different values of damping parameter i.e. mass and effective stiffness of damper. Then dynamic analysis was performed for the different types of cable-stayed bridges.

After the dynamic analysis, different variations have been plotted and the effects of different variations are analyzed.

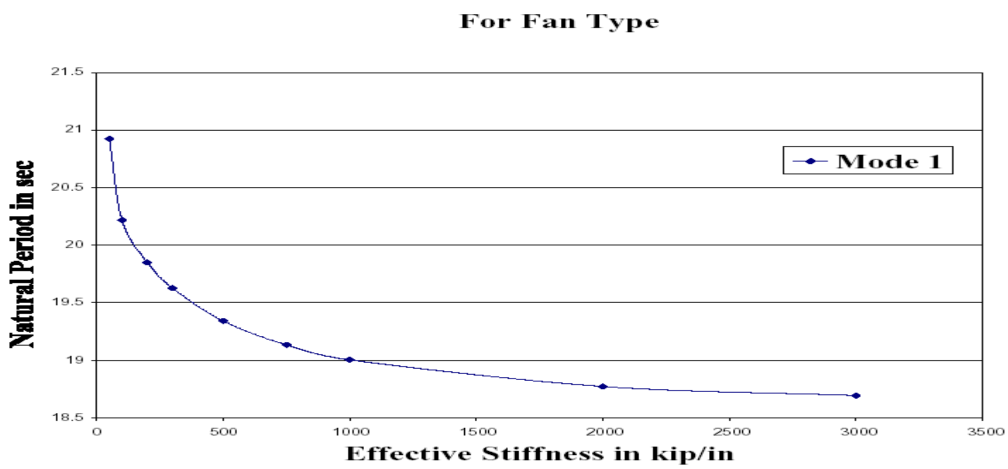


Fig. 7. Natural period vs effective stiffness of damper (for fan type)

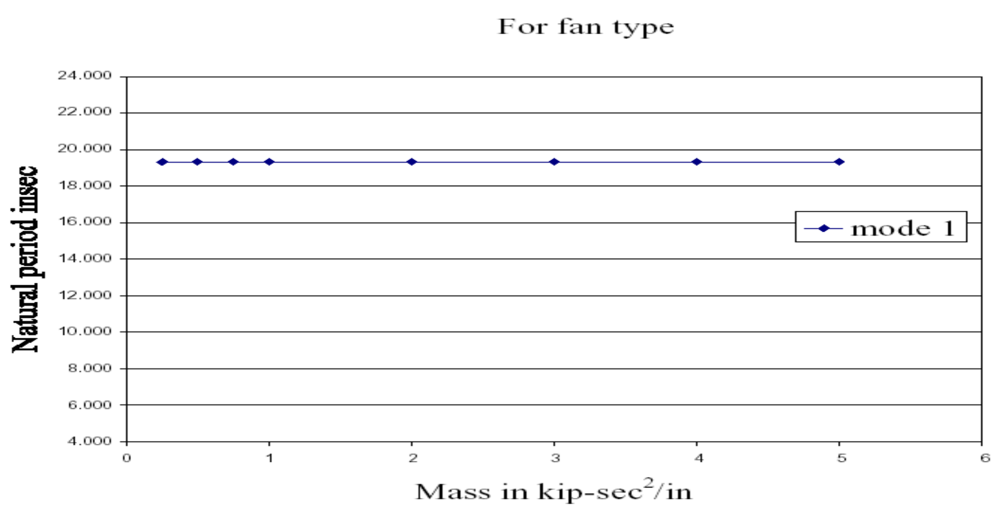


Fig. 8. Natural period vs mass of damper (for fan type)

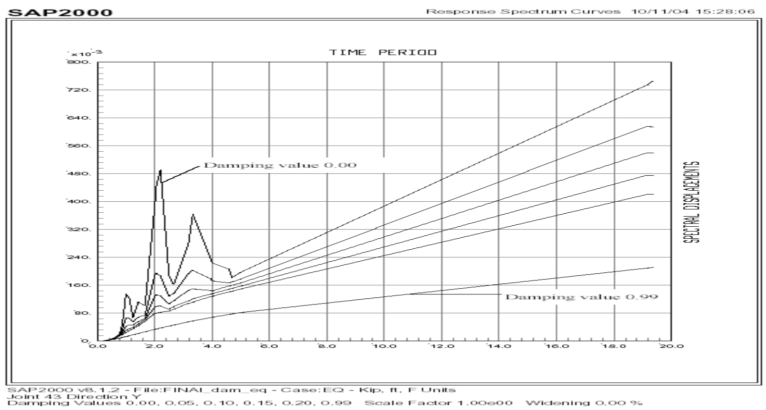


Fig. 9. Response spectrum curve (spectral displacements vs time period)

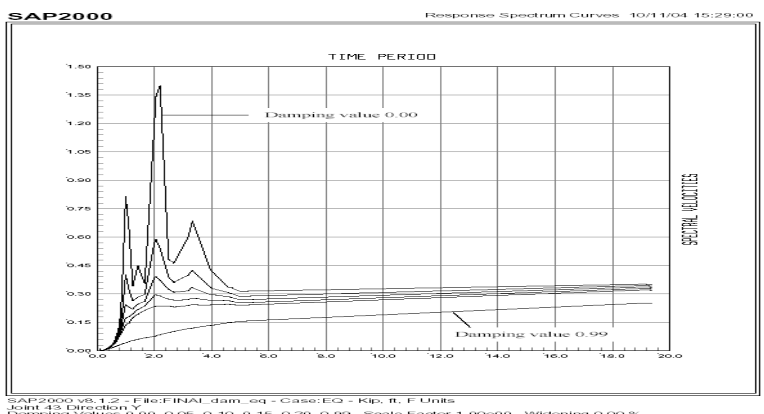


Fig.10. Response spectrum curve (spectral velocity vs time period)

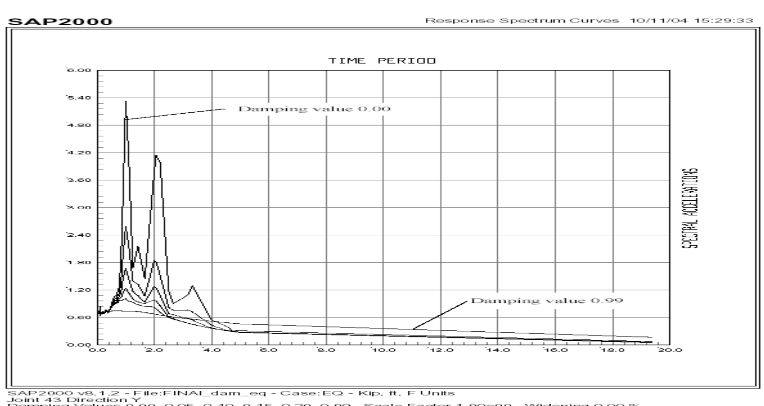


Fig. 11. Response spectrum curve (spectral accelerations vs time period)

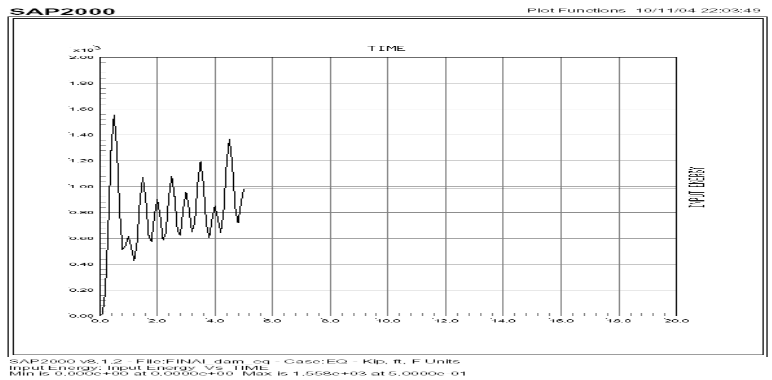


Fig. 12. Plot function analysis (input energy vs time)

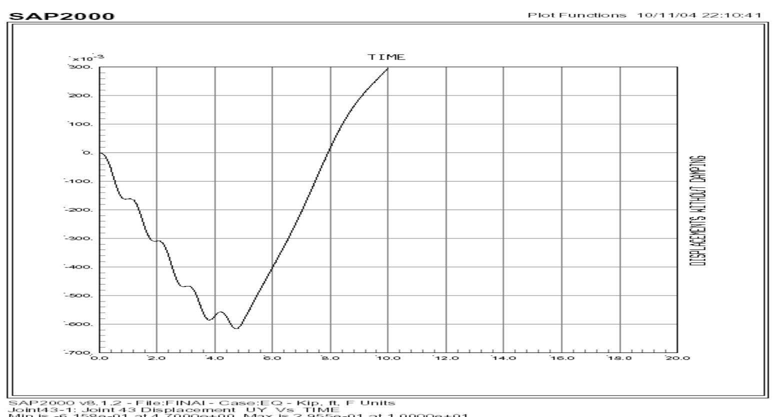


Fig. 13. Plot function analysis (displacements without damping vs time)

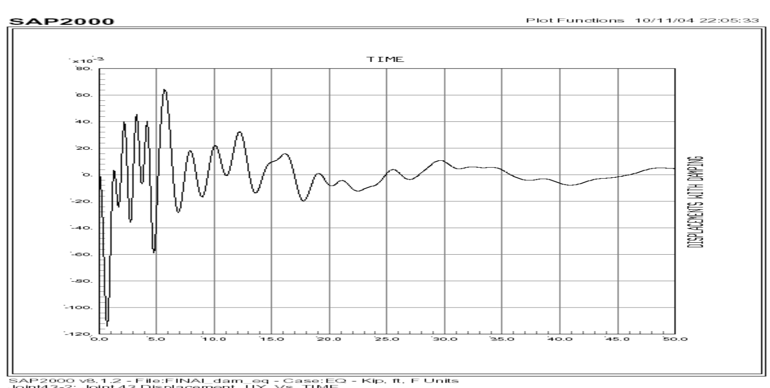


Fig. 14. Plot function analysis (displacements with damping vs time)

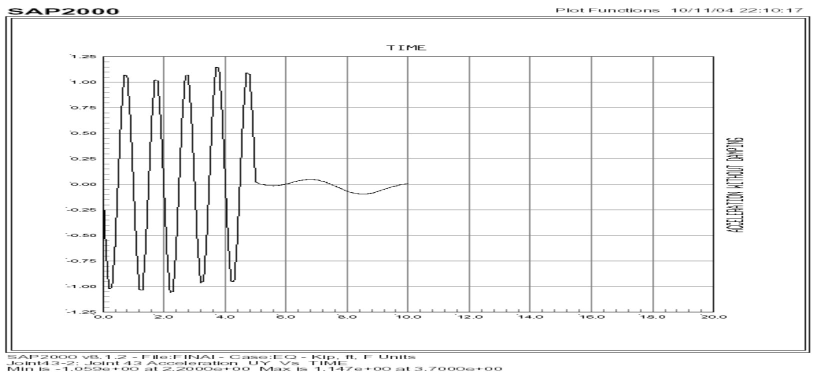


Fig. 15. Plot function analysis (acceleration without damping vs time)

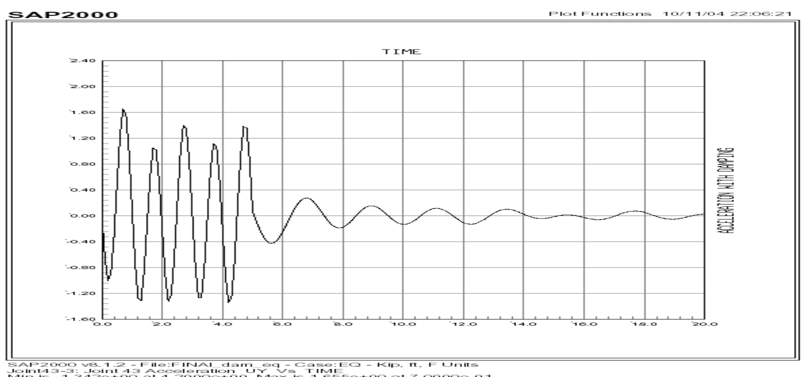


Fig. 16. Plot function analysis (acceleration without damping vs time)

6.1 Effect of effective stiffness of damper on natural period

From Fig. 7. for fan type, it can be seen that natural period decreases with effective stiffness of damper. But the decrease is nonlinear and after a certain value of effective stiffness, natural period does not decrease significantly. After the value of effective stiffness of 87.56 kN/mm (500kip/in), the change of natural period is not significant. Thus it can be concluded that effective stiffness has very significant influence on natural period of the Cable-stayed bridges and the value of effective stiffness of damper can be chosen 87.56 kN/mm (500kip/in).

6.2 Effect of mass of damper on natural period

From Fig. 8 for fan type, it would be observed that natural period shows little change with the change in mass of damper and the plotting curve is straight line i.e. mass of damper has no effect on natural period of the Cable-stayed bridges.

6.3 Response spectrum analysis

From Fig. 9, Fig. 10 and Fig. 11., representating response spectrum curve with different damping values i.e. damping ratio, it is evident that spectral displacements, spectral velocities and spectral acceleration decrease with both the time and the decreasing damping ratio. And when damping ratio is almost critical damping i.e. 100%, then spectral displacements, spectral velocities and spectral acceleration is very small and the curve is almost a straight line. From the analysis it may be said that at the damping ratio of 5% i.e.0.05., the spectral displacements, spectral velocities and spectral acceleration are almost negotiable.

6.4 Plot functions analysis

From fig. 12. it can be observed that after a certain time, input energy variations with time is constant. From fig. 13. and fig. 14., it can be said that displacements decreased significantly due to application of damper. From fig.15. and fig.16. it is evident that ground acceleration decreased substantially due to application of damper.

7. Conclusions

From the studies performed, the following conclusions are apparent:

- By proper selection of the effective stiffness of damper it is possible to significantly influence the natural periods of various types of vibration modes of the cable-stayed bridge. The value of effective stiffness of damper which gives tentative optimum solution is about 87.56 kN/mm (500kip/in).
- Prepared graphical charts for different effective stiffness of damper with natural period can be used as a guideline for selecting the tentative optimum effective stiffness of damper that required in a cable-stayed bridge.
- Dynamic response of the bridges like spectral displacements, spectral velocities, and spectral acceleration with time can be minimized and controlled effectively and efficiently by means of damping.
- The energy dissipation and variations of displacements and ground acceleration with and without damping may also be ascertained from the study.

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