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SLOSHING LIQUID DAMPER INSTALLATION ON A BROADCASTING TOWER AT Mt. WELLINGTON, TASMANIA

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INTRODUCTION

This paper discusses the design, installation and performance of the tuned sloshing dampers to mitigate the dynamic response to wind of the original steel lattice broadcasting tower, at Mount Wellington, Tasmania. The tower was 104 metres high and suffered from severe wind-induced vibrations, after installation of a large cylindrical shroud. The dampers were installed in early 1992. Instrumentation for monitoring of the dynamic response to wind was installed in 1993, and measurements of response were carried out during the winter of 1994. The tower was eventually dismantled in 1997, after erection of a replacement structure.

DAMPER PRINCIPLES AND DESIGN

A tuned sloshing liquid damper (T.S.D.) consists of shallow liquid in a container "sloshing" at a frequency at or near the natural (first mode) frequency of the structure. In the T.S.D., vibration energy is transferred from the tower motion to the kinetic energy of sloshing liquid. A certain percentage of the energy is dissipated during the sloshing action. The two main mechanisms for doing this are : (i) Viscous dissipation in the fluid - in particular in the boundary layers on the base of the container, and (ii) Impacts of breaking waves on the walls of the container.

The action of the T.S.D. is analogous to the tuned mass damper (T.M.D.) but the elements of inertia (mass), stiffness and viscous dissipation are not as clearly defined in the T.S.D. compared with the T.M.D. The clear advantages of the T.S.D. are its simplicity, and hence low cost, and its ease of tuning. The fundamental sloshing frequency is a simple function of the depth of liquid and container width, for a given container shape. Thus for two dimensional motion, the sloshing frequency is given by Equation (1) derived from shallow wave theory :

$$n_D = (1/2\pi)\sqrt{[(\pi g/D) \tanh(\pi h/D)]} \qquad (1)$$

where g is the acceleration due to gravity, h is the height of liquid, and D is the width (diameter) of the container. Equation (1) underestimates the fundamental sloshing frequency for circular containers in which there is three-dimensional motion.

A considerable amount of theoretical and experimental work on T.S.D.'s has been carried out by a group at the University of Tokyo under Professor Y. Fujino [2,3,4]. Experimental work was carried out at Tokyo firstly using free-vibration experiments with circular containers [4]. This study identified as many as six different visual classifications of liquid motion, depending on the h/D ratio and on the amplitude of motion. The fundamental sloshing frequency for sloshing in circular containers was determined by linear potential theory to be :

$$n_D = (1/2\pi)\sqrt{[(1.17\pi g/D) \tanh(1.17\pi h/D)]} \qquad (2)$$

Later experimental work was carried out with a shaking table, i.e. forced vibration, for the purpose of experimentally verifying the mathematical models [5]. A study of the shape and size of the container on the performance of T.S.D.'s was also carried out at Tokyo [6]. Based on a series of free vibration tests at 0.5 Hertz, the "universal' curve shown in Figure 1 was obtained. The ordinate of this curve denoted by $\Delta E/E_n\mu$, is the percentage of kinetic energy loss per cycle per mass ratio. μ is the mass ratio equal to the ratio of the water mass to the effective structural mass. This can be directly related to the critical damping ratio, ζ, by Equation (3) :

$$\zeta = (1/4\pi) \ln \{[1/(1-(\Delta E/E)]\} \quad (3)$$

The abscissa in Figure 1 is the non-dimensional vibration amplitude, α, equal to the ratio of the amplitude to half the container width. A single function as shown in Figure 1 represents all the experimental results from six different damper geometries over a range of geometries. This curve is useful for design purposes. This curve shows that more energy dissipation, i.e. more damping, is obtained when α is low; thus for a given amplitude of vibration and a given mass of fluid, a larger diameter of container is desirable. Thus a single large container of liquid appears more efficient than many small containers. However, for practical reasons, such as available space, this may not always be the best option. Also the "universal" curve shown in Figure 1 needs to be confirmed for larger containers.

FREE VIBRATION TESTING AT CSIRO

A series of experiments were conducted at CSIRO to compare the performance of eight different tuned sloshing dampers [7]. A 60 kg platform was suspended by four cantilevers, the tops of which were bolted into a rigid frame 3 metres in height. Four spherical bearings supported the test platform from the free end of the cantilevers. The cantilevers consisted of four 20 mm diameter threaded bars, 2.5 metres in length, which allowed adjustment to vary the free vibration frequency. For the tests, the frequency was adjusted to be the same as the first mode frequency as the Mount Wellington Tower, i.e. 0.7 Hertz. The following function for non-dimensional energy absorption fits the CSIRO tests well :

$$\Delta E/E_n\mu = 8.5 + 31.5 \exp(-14\alpha) \quad (4)$$

As can be seen from Figure 1, the energy dissipation rates obtained in these tests agree quite well with Japanese data.

INSTALLATION

The values of h and D used in the Mount Wellington tower installation were 510mm and 25 mm respectively. Equation (2) gives a value of n_D of 0.57 Hertz, which is slightly below the first mode natural frequency of the tower. A total of 80 containers were manufactured and installed giving a total mass of liquid of 400 kg. Each damper was partly filled to a depth of 25 mm with a mixture of 2.5 litres of water and 2.5 litres of a commercial anti-freeze containing 93% ethylene-glycol. Individual interlocking dampers were installed at the 87.8 meter level in a total of five stacks. Each stack of dampers was located on a catch tray and held in place by a clamp plate held down by four 16 mm threaded hold-down rods. Dampers were arranged into three stacks of twelve and four stacks of eleven.

ASSESSMENT OF PERFORMANCE

The total damping, or energy-absorbing capacity, of a tower like that at Mount Wellington is comprised of a number of components :i) structural damping, ii) aerodynamic damping, iii) auxiliary damping, such as that provided by a T.S.D. The total damping was measured in this case by the random decrement technique, [8,9]. Figure 2 shows the total damping plotted in the form of a critical damping ratio versus mean velocity obtained from acceleration response records from 1989 (before installation of the T.S.D. system), and from 1994 (after installation of the T.S.D.'s). Only records for mean velocities (at 72 metres height) of 15 m/s or greater were plotted. The damping values were obtained by fitting a straight line relationship to $\log_e a_n$ versus n, where a_n is the amplitude of the n th peak on the random decrement signature. Only those signatures for which a correlation coefficient of 0.99 or higher was obtained were used in Figure 2. This criterion actually resulted in many signatures being rejected usually because of 'beating' effects caused by two closely spaced frequencies.

The aerodynamic damping contribution, is also plotted on Figure 2. This indicates that the total damping without the tuned sloshing dampers installed (1989 data) is dominated by the aerodynamic damping. After the dampers were installed (1994 data), despite the scatter, the Figure indicates an incremental increase in damping of about 0.015, or 1.5% of critical at a mean wind speed of 25-30 m/s. Qualitatively, Telstra during maintenance inspections, found a significant reduction in loosening and loss of structural bolts on the tower in the three winters after the installation of the T.S.D.'s.

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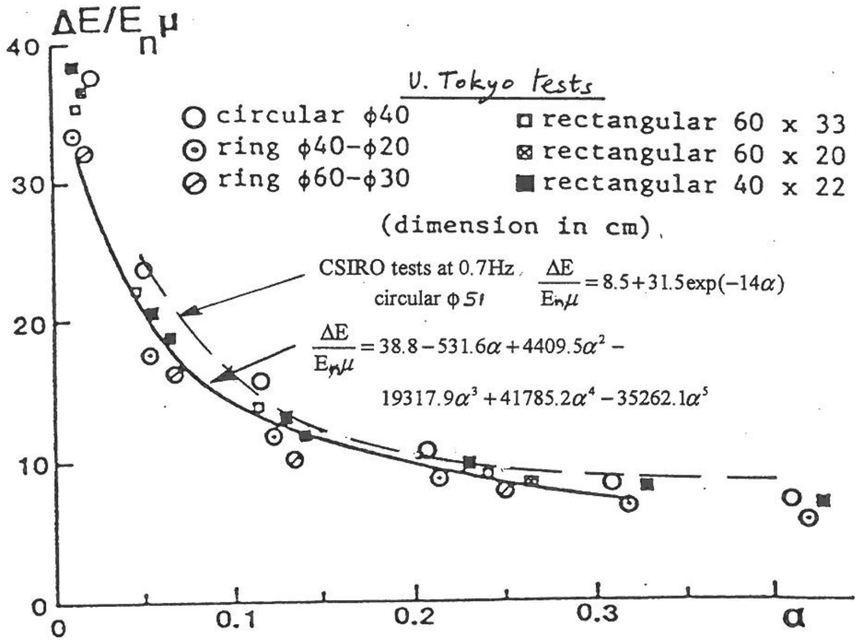

Figure 1. Normalized energy dissipation versus non-dimensional amplitude for various types of sloshing dampers

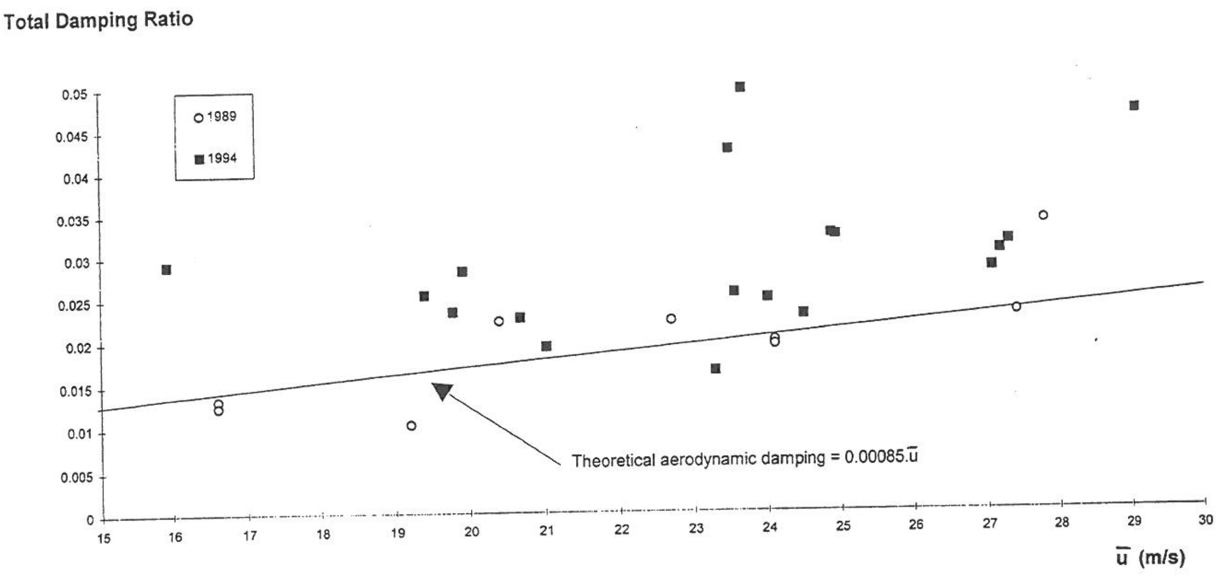

Figure 2. Total critical damping ratio before and after damper installation