DAMPING PROPERTIES AND WIND INDUCED RESPONSE OF A STEEL FRAME TOWER FITTED WITH LIQUID COLUMN VIBRATION ABSORBERS.

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1. INTRODUCTION

Trends in modern tall building design and construction have allowed an increase in the number of civil engineering structures that are relatively light and flexible. These structures tend to have low levels of intrinsic damping and can be especially prone to high resonant accelerations when subject to wind loading, which may cause occupant discomfort or hinder the function of motion sensitive equipment. One effective method of mitigating the effects of wind excitation is to install passive vibration absorbers into a structure .

Liquid Column Vibration Absorbers (LCVA) are passive vibration absorbers comprised of vertical and horizontal liquid columns of nominally different cross-sectional areas accommodated in a rigid container. A LCVA absorbs the vibrational energy of a structure and utilises the viscous interaction between the LCVA liquid and rigid container to dissipate this energy. Further energy dissipation occurs due to turbulence induced in the LCVA liquid as it moves between the transition of the horizontal and vertical columns, as well as the gravitational restoring force acting on the displaced liquid column. A LCVA can be configured either as a uni-directional vibration absorber, similar to a traditional Tuned Liquid Column Damper (TLCD) [5], or as a bi-directional vibration absorber capable of mitigating structural vibrations in the direction of two principal axes[4].

Twenty bi-directional LCVA units were installed on a full scale steel frame communications tower, shown in Figure 1, in May of 1995 as part of an ongoing field investigation of the tower [1],[2] and [3]. This paper will outline the design of the LCVA units fitted to the tower, and their affect upon the damping properties and wind induced response of the tower. Theoretical estimates of tower damping and wind induced response with and without the LCVAs installed are also presented.

2. LCVA DESIGN AND INSTALLATION.

The nominally different horizontal and vertical column cross-sectional areas of an LCVA allows the LCVA natural frequency to be controlled by its geometrical configuration rather than the length of the liquid column only [4]. This allows a LCVA the versatility of being accommodated within the useable space of an existing structure. The LCVAs were designed to mitigate vibrations corresponding to the first mode of vibration of the tower (1.05 Hz at the time of installation). To achieve this in the limited available space the LCVAs were configured as shown in Figure 2 and the exterior dimensions of the LCVA were approximately 500 × 500 × 300 mm. The horizontal column lengths in both axial directions, denoted as d_x and d_y in Figure 2, were 450 mm; the horizontal column thickness, denoted as T_h in Figure 2, was 45 mm; the vertical column thicknesses in both axial directions, denoted as T_{vx} and T_{vy} in Figure 2, were 23 mm. Each LCVA was tuned to the same natural frequency by maintaining a common vertical column height, denoted as h_v in Figure 2, which was confirmed as appropriate in free-vibration experiments prior to installation.

Each LCVA contained baffles to eliminate wave actions in the vertical columns, identified in [6], and did not contain orifices. Without orifices, the LCVA liquid damping ratio was expected to be less than optimum [4], although the structural damping of the tower prior to LCVA installation was large enough to suggest that this would not be problematic. Furthermore, by not including orifices in the LCVA design the LCVA liquid damping ratio was such that the effects of a Multiple LCVA (MLCVA) could be investigated in future studies.

Twenty such LCVA units were fabricated at the University of Sydney from UV resistant PVC and installed by research staff and students of Wind Engineering Services at the 57 m level of the tower. The total mass of the installed LCVAs was approximately 280 kg, providing an absorber mass approximately 1.2% of the first mode generalised mass of the tower and 0.2% of the total tower mass.

3. PREDICTED AND MEASURED TOWER DAMPING

Free-vibration tests were performed on the tower prior to the installation of the LCVAs to obtain a structural damping decay curve for the first mode of vibration in the east-west axial direction as shown in Figure 3. The tower was excited by human movement in time with a metronome at the natural frequency of the tower. Forcing ceased once the tower was resonating, at which time the tower was allowed to vibrate freely until it came to rest. Free-vibration tests were performed during still atmospheric conditions to eliminate any aerodynamic effects.

Figure 4 is the free-vibration decay curve in the east-west direction derived from modelling the tower as a single degree of freedom structure in which the modes of vibration of the tower are assumed to be sufficiently separated to prevent any interaction, and structural damping is assumed to be linear viscous damping. In Figure 3 structural damping in the east-west direction can be observed to be approximately linear and can be satisfactorily modelled assuming linear viscous damping 0.55% of critical.

Subsequent free-vibration tests were performed with the LCVAs installed to determine the ability of the LCVAs to mitigate structural vibrations and increase overall damping, the results of which are presented in Figures 5 for the east-west direction. Included in Figure 6 is the free-vibration decay curve derived from modelling the tower and the LCVAs as a two degree of freedom system. In this model the damping of the tower and the LCVAs were assumed to be linear viscous damping, although LCVA liquid damping has been found to be non-linear and dependent on Reynolds number [6]. This allowed the free-vibration decay of the tower with LCVAs installed to be predicted with reasonable accuracy, and where discrepancies in the east-west direction can be attributed to the non-linearity of LCVA liquid damping.

The effective damping of the tower in the east-west direction was increased to the equivalent of approximately 2.5% of critical after the LCVAs were installed. The predicted value of effective tower damping in the east-west direction is approximately 2.7% of critical, being within 10% of the measured value. The predicted value of effective tower damping are larger than the measured value because of the non-linearity of LCVA liquid damping.

4. PREDICTED AND MEASURED WIND INDUCED TOWER RESPONSE

As outlined in [1], the Prospect Tower was fitted with anemometers and accelerometers at the top of the tower, to establish correlation between wind speed and tower resonance. The wind-induced response of the tower was then monitored before and after the installation of the LCVA units.

A random decrement analysis [3] was performed upon 8 minute samples of wind induced acceleration records to measure Prospect Tower damping under wind loading. Total damping in the along-wind direction is plotted against the simultaneously recorded mean wind speed of each sample in Figure 7. At wind speeds beyond 10 m/s, the magnitude of tower damping lies close to the values obtained from free-vibration decay tests (about 0.7% before LCVAs and 3% after LCVAs). Below 10 m/s there is little additional damping offered by the LCVAs. At low tower acceleration (<2 mg), it is considered that the induced amplitude and Reynolds number of the liquid column are too low to mitigate energy.

The relationship between the standard deviation of along-wind tower acceleration response and mean wind speed is shown in Figure 8. One minute samples of acceleration data are presented before and after the installation of the LCVAs. At higher wind speeds, the response of the tower is seen to be almost halved after LCVA installation. A similar reduction was observed for cross-wind acceleration. Included in Figure 8 are predicted root-mean-square resonant accelerations for the first mode of the Prospect Tower. These curves were obtained using a gust factor approach as detailed in [2]. Structural damping values of 0.7%

and 3% of critical damping were used to estimate rms resonant acceleration before and after LCVA installation respectively.

Figure 9 illustrates power spectra of along-wind acceleration for the first mode of the Prospect Tower before and after LCVA installation. Both acceleration spectra were induced by winds of almost identical magnitude and yaw as averaged over 820 seconds (2^{14} samples, 20 Hz sample frequency). The peak at the resonance point observed before installation (1.05 Hz) has decreased considerably. Since the vibration system including the LCVAs may be considered as a two degree of freedom system, there are two reduced resonance points following installation. Characteristically, the reduced peaks are above and below the original resonance peak.

5. CONCLUSIONS

The ability of 20 Liquid Column Vibration Absorbers (LCVA) to mitigate the wind-induced vibrations of a full-scale steel frame tower was investigated. The following conclusions can be made from the results:
(1) The versatile geometrical configuration of a LCVA allows a required liquid column effective length to be achieved for a particular natural frequency even when useable space is limited. Individual small stackable LCVA units may be arranged in the useable space to provide an appropriate mass ratio.
(2) The installation of a LCVA system in a tall structure is an effective method of increasing the equivalent structural damping.
(3) The effects of a LCVA on the free-vibration decay of a structure can be adequately modelled as a two degree of freedom system with linear viscous damping provided that the modes of vibration of the structure are sufficiently separated to prevent interaction, and provided that structural damping is predominantly linear viscous damping.
(4) The wind induced resonant response of the full scale tower was almost halved following LCVA installation.

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REFERENCES

(1) Glanville, M.J., and Kwok, K.C.S., "Dynamic characteristics and wind induced response of a steel frame tower", Journal of Wind Engineering and Industrial Aerodynamics, (1995), Vol 54/55, pp. 133-149.
(2) Glanville, M.J., and Kwok, K.C.S., "Wind induced deflections of free-standing lattice towers", Accepted for publication, Engineering Structures.
(3) Glanville, M.J., Kwok, K.C.S., and Denoon, R.O., "Full-scale damping measurements of structures in Australia", Accepted for publication, Journal of Wind Engineering and Industrial Aerodynamics.
(4) Hitchcock, P.A., Kwok, K.C.S., Watkins, R.D., Samali, B., "Characteristics of Liquid Column Vibration Absorbers (LCVA) - Parts 1 and 2", submitted for possible publication to J. Engineering Structures.
(5) Sakai, F., Takaeda, S., Tamaki, T., "Tuned Liquid Column Damper - New Type Device for Suppression of Building Vibrations", Vol. 2, Proc. of Int. Conf. on Highrise Buildings, Nanjing, (1989), pp. 926-931.
(6) Watkins, R.D., Hitchcock, P.A., "Model Tests on a Two-Way Liquid Column Vibration Absorber", Research Report No. 656, School of Civ. and Min. Eng., University of Sydney, (1992).

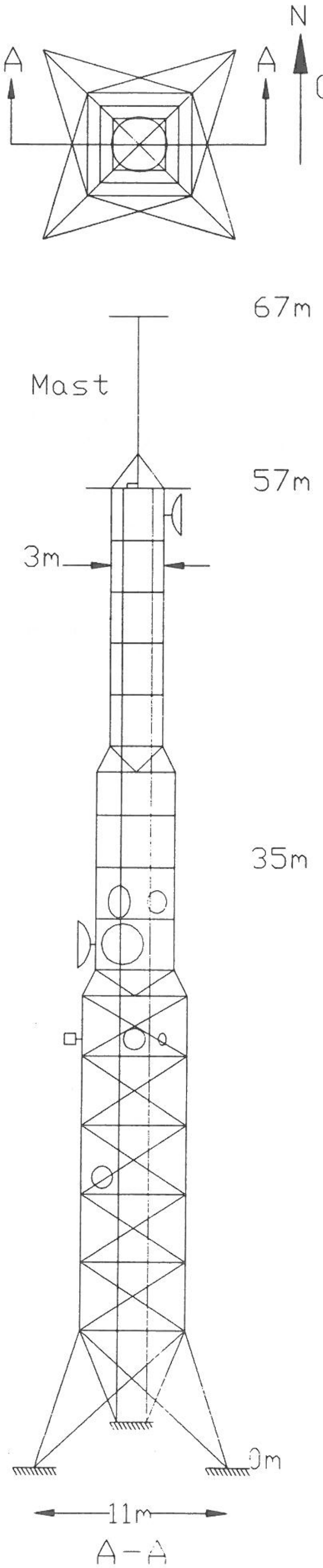

Figure 1. General Arrangement of the Prospect Tower.

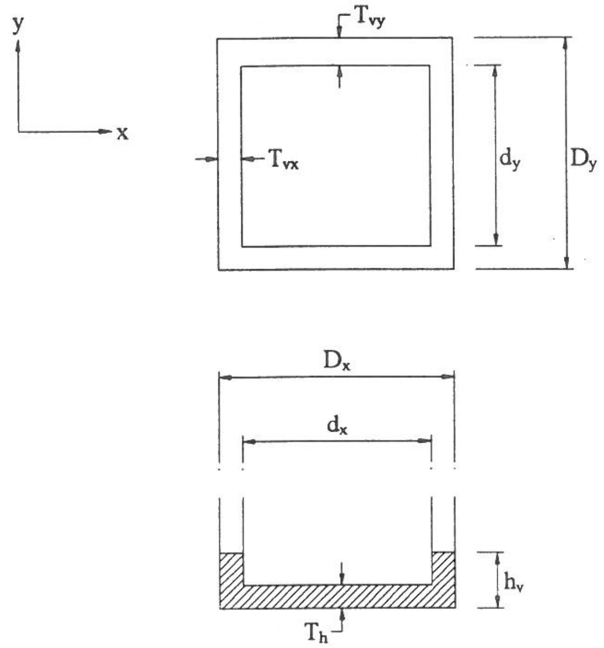

Figure 2. Bi-Directional LCVA.

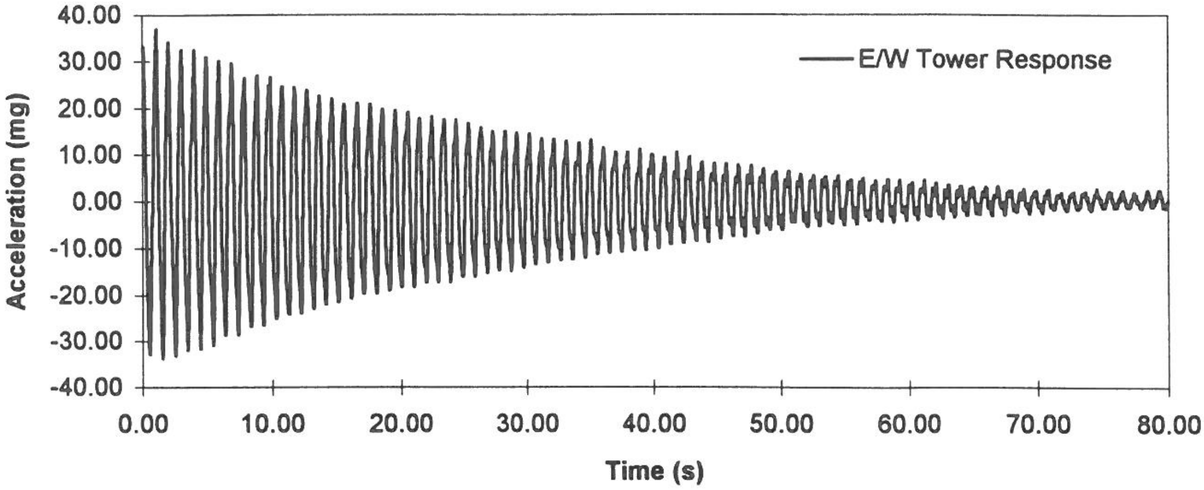

Figure 3. Measured Tower Free-Vibration Decay without LCVAs.

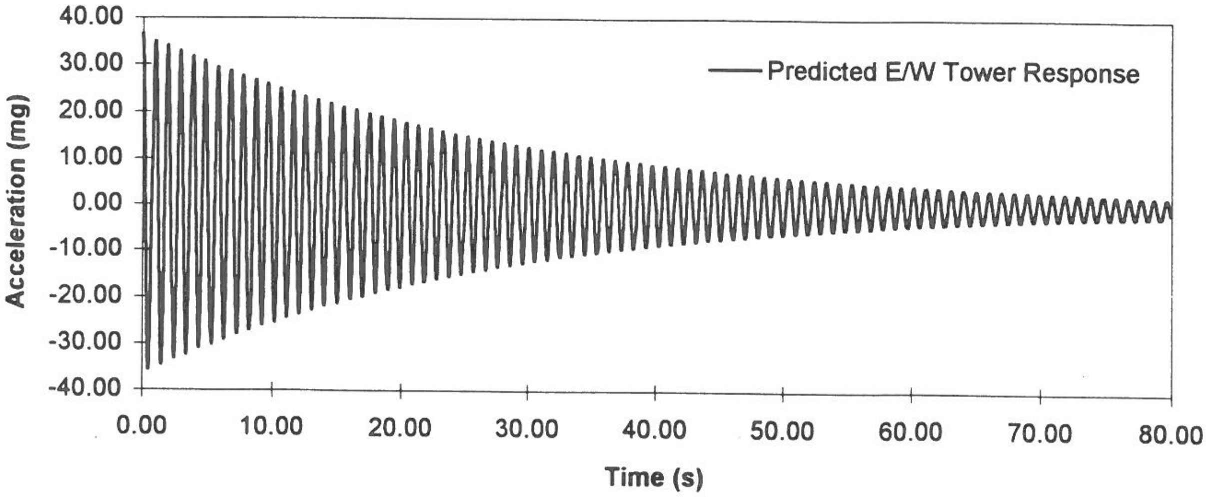

Figure 4. Predicted Tower Free-Vibration Decay without LCVAs.

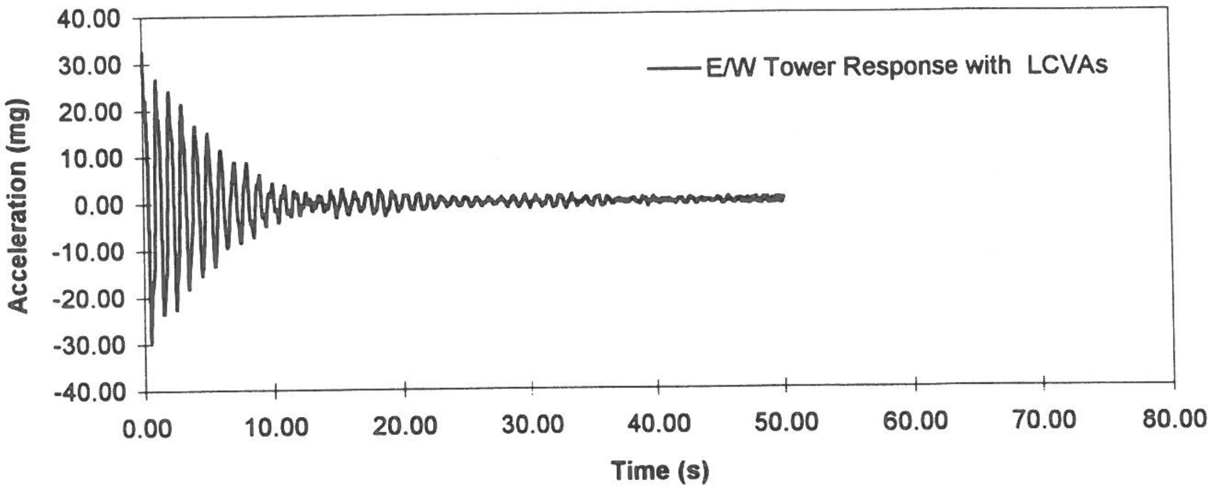

Figure 5. Measured Tower Free-Vibration Decay with LCVAs.

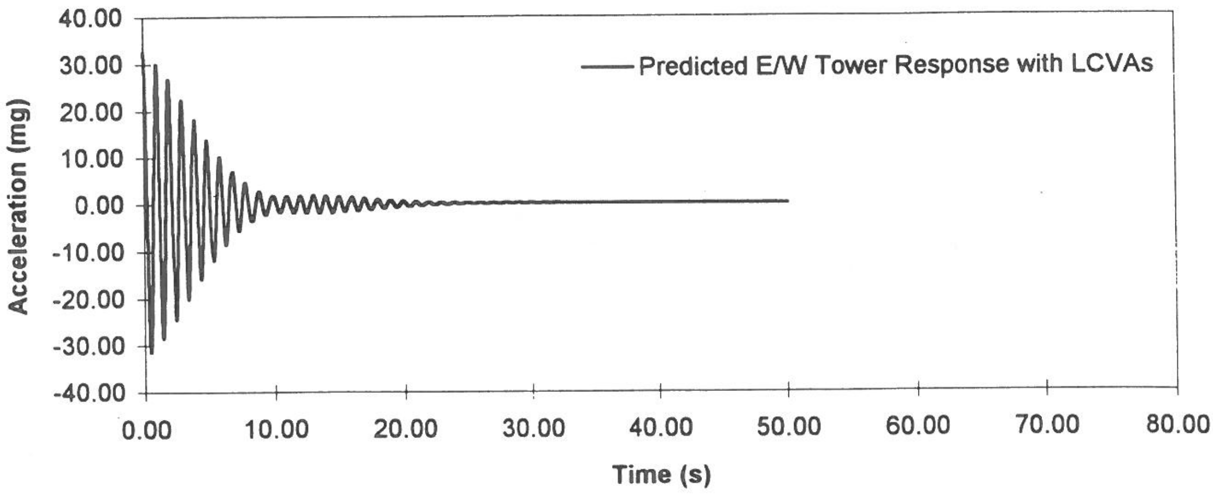

Figure 6. Predicted Tower Free-Vibration Decay with LCVAs.

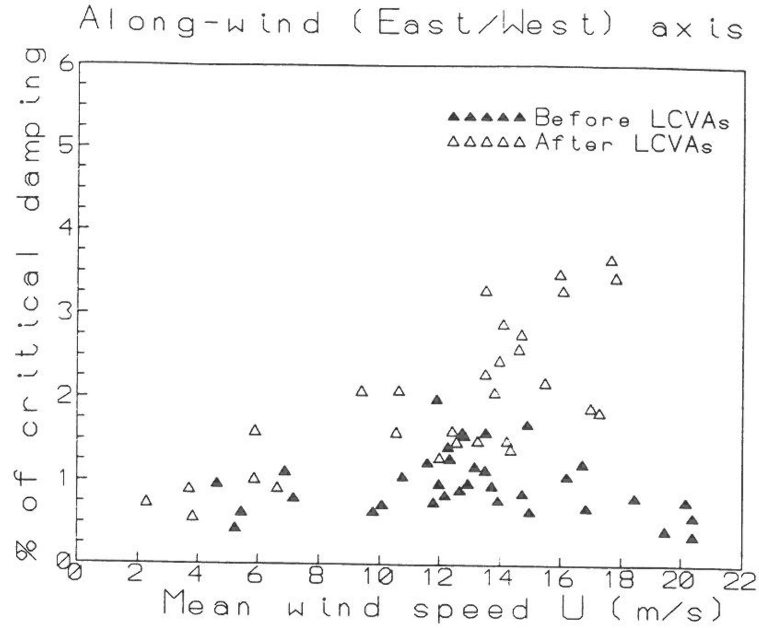

Figure 7. % of critical damping as obtained from a random decrement analysis versus mean wind speed.

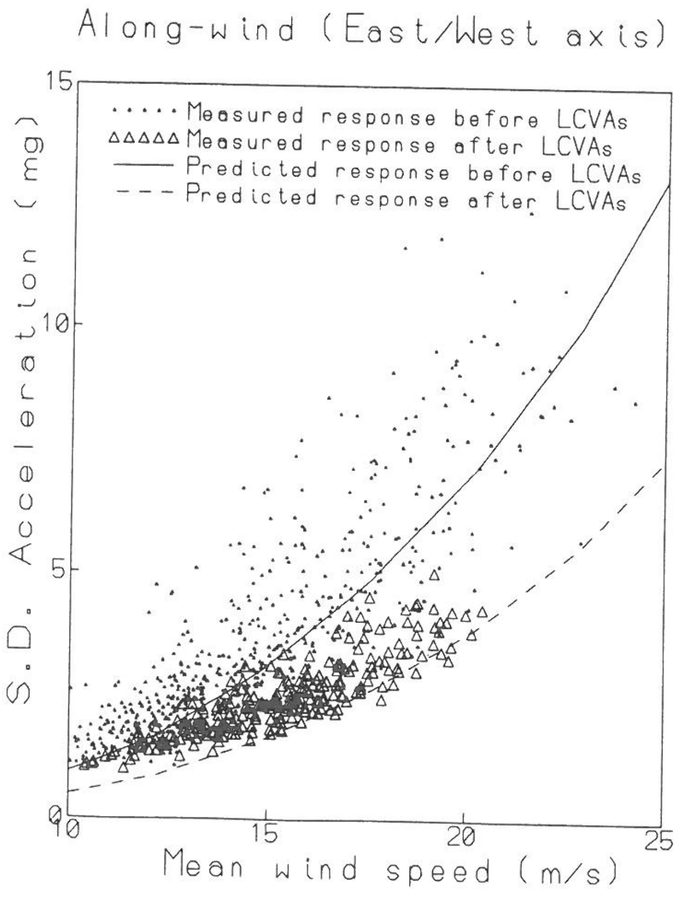

Figure 8. Standard deviation of tower acceleration response versus mean wind before and after LCVA installation

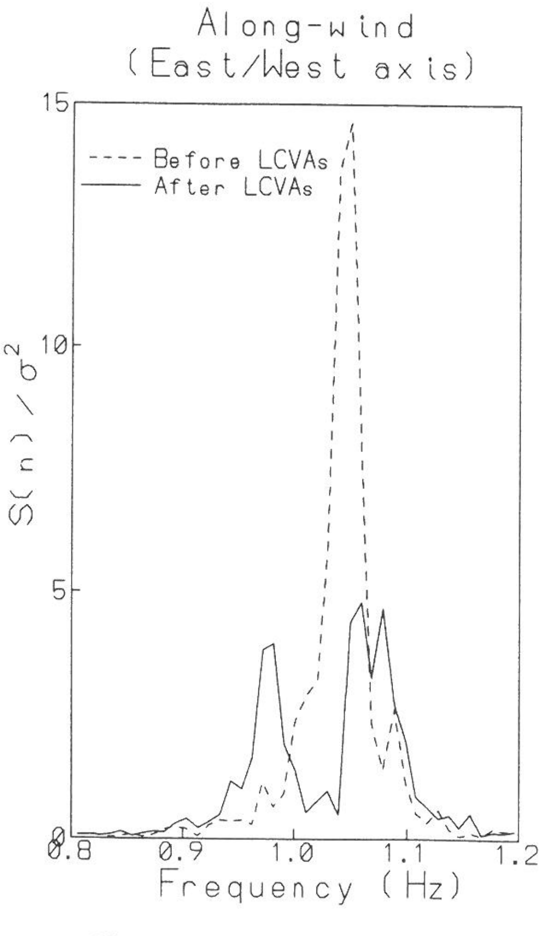

Figure 9. Spectral density of wind induced acceleration response before and after LCVA installation