THE EFFECTIVENESS OF A MULTIPLE LIQUID COLUMN VIBRATION ABSORBER

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1. INTRODUCTION

A Liquid Column Vibration Absorber (LCVA) is a passive vibration control device which utilises the viscous interaction between a liquid and a rigid container to absorb and dissipate the vibrational energy of a primary structure. Further energy is dissipated through the transition effects caused by the action of the absorber liquid as it moves between the vertical and horizontal sections of a LCVA, as well as the gravitational restoring force acting on the liquid.

To date, supplementary vibration absorbing devices have generally been considered as systems consisting of a mass, or masses, which are tuned to a specific single frequency only. However, a proven alternative to the use of a single tuned vibration absorber is the use of a multiple vibration absorbing system as investigated by Fujino and Abe(1), in the case solid masses (MTMD), and Sun and Fujino(2), in the case of Multiple Tuned Liquid Dampers (MTLD). Further research has been undertaken into a Multiple Tuned Liquid Column Damper system by Samali et.al.(3) which indicated that this type of system is effective in mitigating structural vibrations caused by small to moderate earthquakes. Each of these studies demonstrated that the respective multiple damping systems were largely insensitive to mistuning of small magnitudes, which is an important aspect when considering the practical application of any type of supplementary vibration absorber.

Initial studies into a Tuned Liquid Column Damper (TLCD), a device which utilises the energy dissipation mechanisms detailed above, were performed by Sakai et.al.(4). Watkins(5), and Watkins and Hitchcock(6),(7), adapted the TLCD to develop the LCVA, where the LCVA does not necessarily contain orifice restrictors, and the horizontal and vertical cross-sections nominally have different cross-sectional areas.

Hitchcock et.al.(8)showed that the ratio of vertical to horizontal cross-sectional area, the horizontal length of the LCVA and the vertical reservoir liquid depth are all important factors in controlling the free-vibration frequency of the LCVA. As a result, the LCVA can be readily configured to form a Multiple Liquid Column Vibration Absorber (MLCVA). A MLCVA was tested in several configurations and its performance was evaluated through comparisons with theoretical results for single LCVAs.

2. EXPERIMENTAL CONFIGURATION

2.1 MLCVA Design

The MLCVA was rigidly constructed from perspex and consisted of five individual liquid columns which, when containing the appropriate volume of fresh water, was approximately 5% of the total mass of the primary structure and which had a critical damping ratio of approximately 0.035. The configuration of the device is shown schematically in Figure 1, where each horizontal section thickness was 0.029m and each vertical section thickness was 0.040m, and the horizontal lengths of each individual LCVA were different. The interior horizontal lengths ranged from 0.610m to 0.954m. By configuring the MLCVA in this fashion, it was possible to make use of the interior space which would not normally be utilised in the case of a single LCVA. Furthermore, the range of free-vibration frequencies available by simply altering the depth of liquid in the vertical reservoirs of a single LCVA was not sufficient for the desired design.

A design approach similar to that outlined by Sun and Fujino(2) was used. The vibration absorber is characterised by three quantities, these being the central frequency (f_0), the frequency band (ΔR) and the frequency spacing (β_i). For a MLCVA with N individual liquid columns, these are defined as :

$$f_0 = \frac{(f_N - f_1)}{2} \tag{1}$$

$$\Delta R = \frac{(f_N - f_1)}{f_0} \tag{2}$$

$$\beta_i = f_{i-1} - f_i \tag{3}$$

The definition of the central frequency implies that an odd number of vibration absorbers should be used so that they are distributed evenly about the central frequency. Furthermore, the central frequency and the free-vibration frequency of the primary structure (f_s) are not necessarily the same. Any difference between these two frequencies is defined by the off-tuning factor :

$$\Delta\gamma = \frac{f_s - f_0}{f_0} \tag{4}$$

The design of the MLCVA allowed the investigation of different frequency bands. Initially, the frequency band was chosen to be 0.2, which implies that :

$$0.90 \le \frac{f_i}{f_0} \le 1.10 \tag{5}$$

Subsequent tests involved changing the frequency band to 0.15, and in both cases the frequency spacing was constant.

2.2 Testing Platform

Each MLCVA configuration was tested on a primary structure consisting of a four-point suspended pendulum, where the free-vibration frequency was controlled through the application of tension springs. This type of structure has been used in previous experimental studies of single LCVAs and is also presented schematically in Figure 1. The primary structure had a mass of approximately 850kg with a free-vibration frequency of 0.64Hz and a critical damping ratio of 0.0010.

Frequency-sweep tests were used to investigate each configuration of MLCVA. This type of test involves the application of a constant amplitude sinusoidal load to the primary structure and incrementally increasing the load frequency through a range about the free-vibration frequency of the primary structure. The displacement of the primary structure corresponding to each load frequency was measured.

3. COMPARISON OF MLCVA AND SINGLE LCVA

3.1 Theoretical Single LCVA

For the purposes of comparing the performance of the MLCVA with a single LCVA, a theoretical model developed by Watkins and Hitchcock(7) for a single LCVA was used. In this model, the LCVA is treated as a solid mass with its own characteristic natural frequency and damping. These quantities, and the LCVA mass, were taken to be the same as the values measured from experimental work. The model is shown in Figure 2.

3.2 Experimental Results of MLCVA

The simplest method of demonstrating the effectiveness of any vibration absorber is to compare the response of the primary structure with and without the vibration absorber installed. Such a comparison is presented in Figure 3 which includes the responses of the primary structure without a vibration absorber, with a theoretical single LCVA and with a tuned MLCVA installed. In this figure, the load frequency is normalised against the free-vibration frequency of the primary structure, termed the load frequency ratio, and the dynamic displacement of the primary structure is normalised against the static displacement of the primary structure, and is termed the amplification ratio.

The response of the primary structure without a vibration absorber installed displays the typical single degree of freedom (SDOF) behaviour, with the largest displacement occurring at a load frequency ratio of approximately 1.0. This load frequency ratio corresponds to the free-vibration frequency of the primary structure. It can be seen quite clearly that the maximum displacement of the undamped case is extremely large.

In contrast to this, the responses of the primary structure with both the theoretical single LCVA and the MLCVA installed are markedly reduced. The response of the primary structure with the theoretical single LCVA installed exhibits the characteristic response where two peak displacements occurred, the first at a frequency less than the free-vibration frequency of the primary structure, and the second at a frequency greater than the free-vibration frequency of the primary structure. The single LCVA in this case was close to being optimally tuned, where the tuning ratio was approximately 0.98. Consequently, the greatest response reduction occurred at a load frequency ratio corresponding to this value.

The response of the primary structure with the MLCVA installed demonstrated a similar reduction in displacement, however, with two significant differences. Whereas the single LCVA configuration caused two distinct peak displacements, the MLCVA configuration eliminated these peaks, but did not provide as large a reduction in response close to the free-vibration frequency of the primary structure. It can also be noted that the MLCVA response was always less than the undamped response, while the single LCVA response was larger in the vicinity of the two peak displacements, although still significantly less than the peak displacement of the undamped response.

A closer inspection can be made of the MLCVA performance in Figure 4, where the effects of tuning the central LCVA (LCVA3) were investigated by varying the depth of liquid in the vertical reservoirs. The depth of liquid in the other LCVAs remained constant and the frequency band was 0.2. While each of the tuning ratios provided similar responses, it can be seen that the best overall performance occurred when LCVA3 had a tuning ratio of 0.99, which corresponded to a depth of 0.065m. Furthermore, it is shown in Figure 5 that all configurations tested reduced the peak displacements below that expected from the single LCVA.

4. EFFECT OF MISTUNING

It has been widely stated that one of the most attractive features of the multiple vibration absorber systems are their ability to remain largely insensitive to mistuning. As part of the preliminary study of mistuning the MLCVA, the lowest frequency LCVA (LCVA1) and highest frequency LCVA (LCVA5) were deliberately, and opposingly, mistuned by altering the depth of liquid in the vertical reservoirs. The overall mass and damping of the MLCVA were maintained at constant values, while the tuning ratio for LCVA3 was maintained at a value of 0.99. In the first mistuning case, the frequency of LCVA1 was increased and the frequency of LCVA5 was decreased, and both were mistuned by approximately 4%. The results of this test are presented in Figure 6, where the performance of the MLCVA was compared to a similarly mistuned theoretical single LCVA. Except in the vicinity of the natural frequency of the single LCVA, the MLCVA generally provided greater response reduction, while the peak displacement was significantly less for the MLCVA.

The second case of mistuning involved decreasing the frequency of LCVA1, and increasing the frequency of LCVA5. The results of this test are presented in Figure 7. In this figure the performance of the mistuned MLCVA was compared with the tuned MLCVA in which the frequency band was 0.2. It is clear from Figure 7 that the tuned and mistuned MLCVA configurations provided very similar response reductions.

5. EFFECT OF FREQUENCY BAND

In their study on the MTLD, Sun and Fujino$^{(2)}$ examined the response reduction provided to a primary structure by MTLDs configured to frequency bands of 0.1, 0.2 and 0.4. A frequency band of 0.4 was found to provide less response reduction than a single TLD, while it was stated that a MTMD of 1% mass ratio has a theoretical optimum frequency band of 0.122. In each of those cases the central tuning ratio of the MTMD was 1.00.

As stated previously, the initial frequency band studied for the MLCVA was 0.2. Using the same MLCVA container and choosing the appropriate depths of liquid in each of the individual LCVAs, the frequency band was reduced to 0.15 while the same overall mass ratio and damping for the MLCVA was maintained. The appropriate choice of liquid depth was facilitated by consulting the graphs in Figure 8. Each of these graphs agreed to within 4% of the predicted free-vibration frequency values, therefore allowing the desired configuration to be easily designed. In both cases, the tuning ratio of LCVA3 was 0.99.

A comparison between the performance of both configurations is made in Figure 9. In the case where the frequency band was 0.15 the peak displacements were larger than the peak displacements corresponding to a frequency band of 0.2. This behaviour appears to be contrary to that predicted by Sun and Fujino(2). The MLCVA with frequency band 0.15 provided similar response reduction to the single LCVA. However, the MLCVA provided greater reduction of peak displacements while the single LCVA provided greater reduction of primary structure displacement in the vicinity of the free-vibration frequency of the primary structure.

6. CONCLUSIONS

A preliminary study was undertaken to determine the effectiveness and potential of a Multiple Liquid Column Vibration Absorber (MLCVA) in mitigating the vibrations of a primary structure when excited by a constant amplitude sinusoidal load. The following conclusions can be made from the results :

(1) The MLCVA has the potential to mitigate the vibrations of a primary structure.
(2) An appropriately tuned MLCVA can provide greater reductions of the peak displacements of a primary structure than an optimised single LCVA with the same mass and damping.
(3) The MLCVA has displayed the potential to be insensitive to mistuning.
(4) A MLCVA with a frequency band of 0.2 can provide greater reduction of peak displacements than a MLCVA with a frequency band of 0.15.
(5) Because the configuration of the MLCVA is more compact than the configuration of a single LCVA, a larger mass can be provided more easily using a MLCVA.

7. REFERENCES

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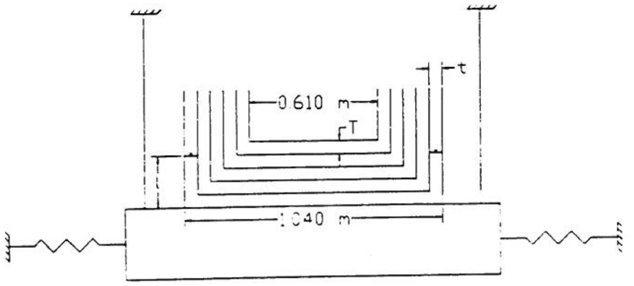

Figure 1. Experimental Configuration

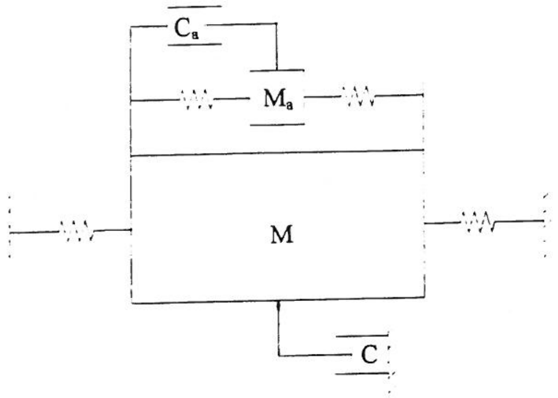

Figure 2. LCVA Theoretical Model

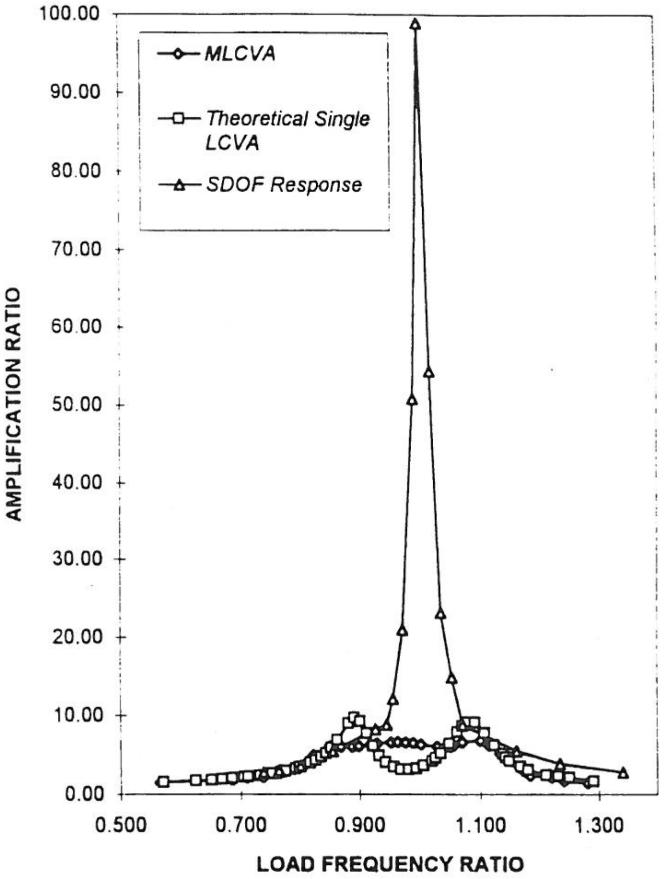

Figure 3. Primary Structure Response

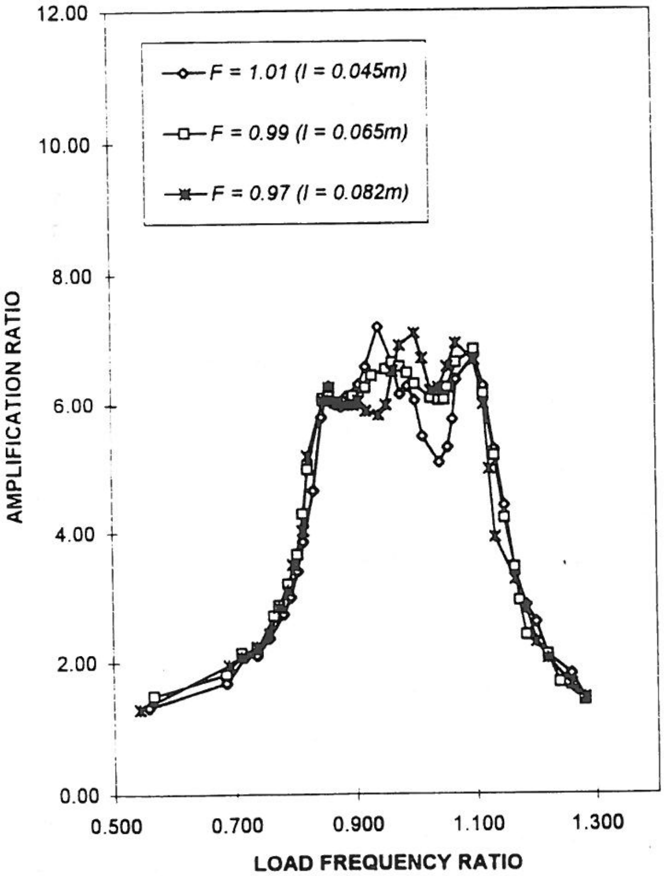

Figure 4. Tuning LCVA3

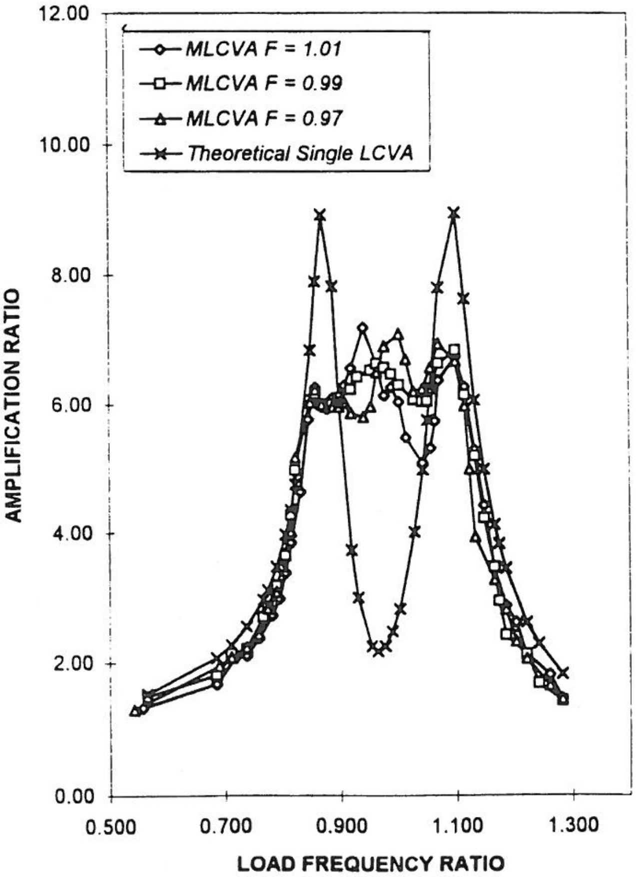

Figure 5. MLCVA vs. LCVA

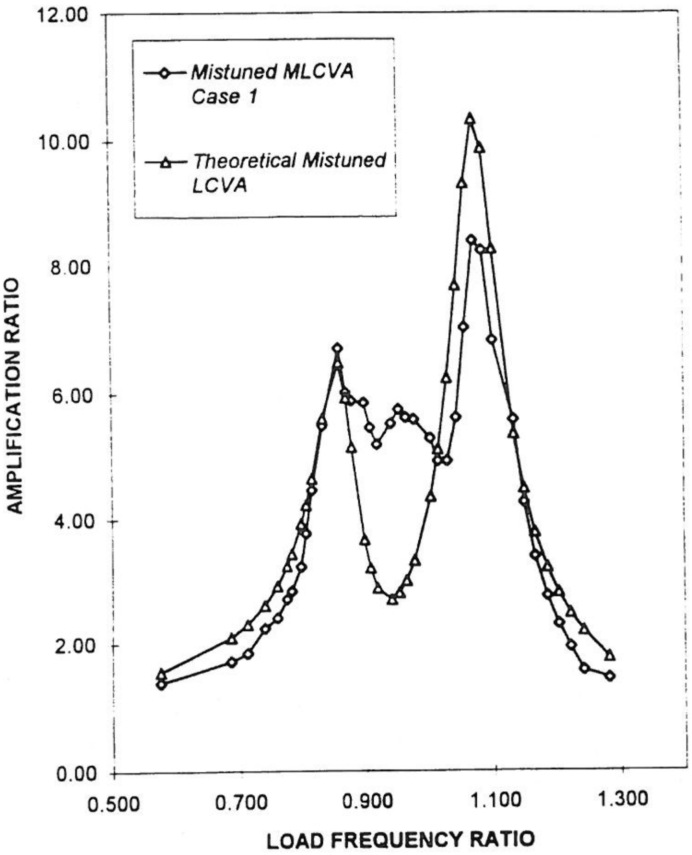

Figure 6. Mistuned Case 1

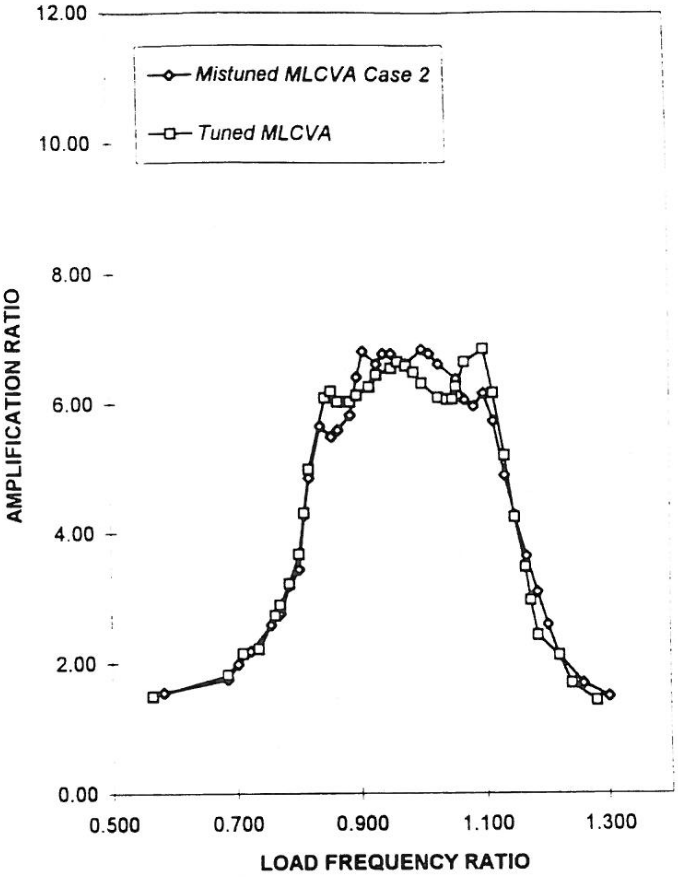

Figure 7. Mistuned Case 2

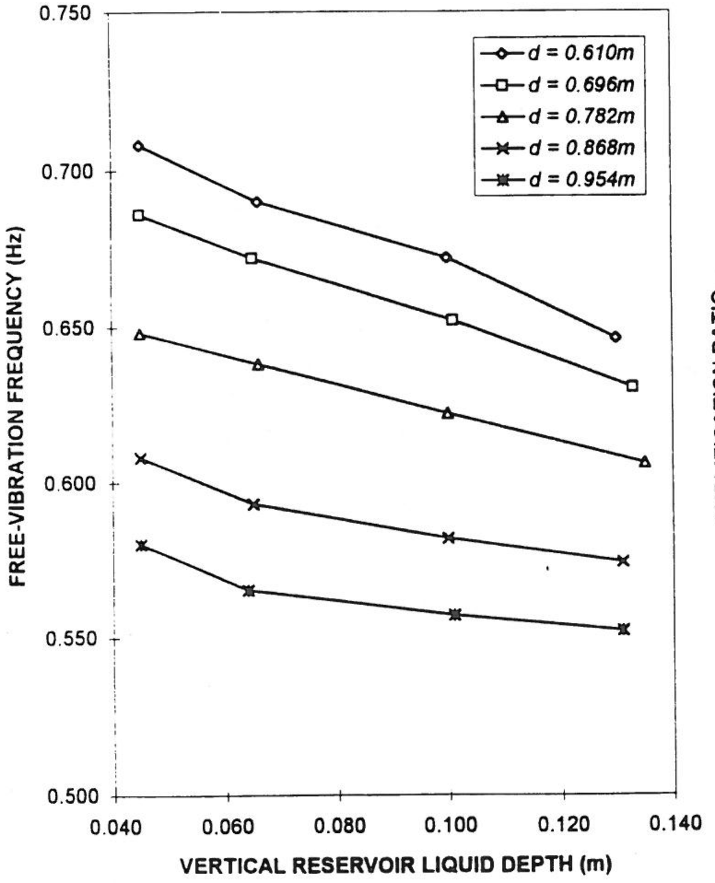

Figure 8. MLCVA Frequencies

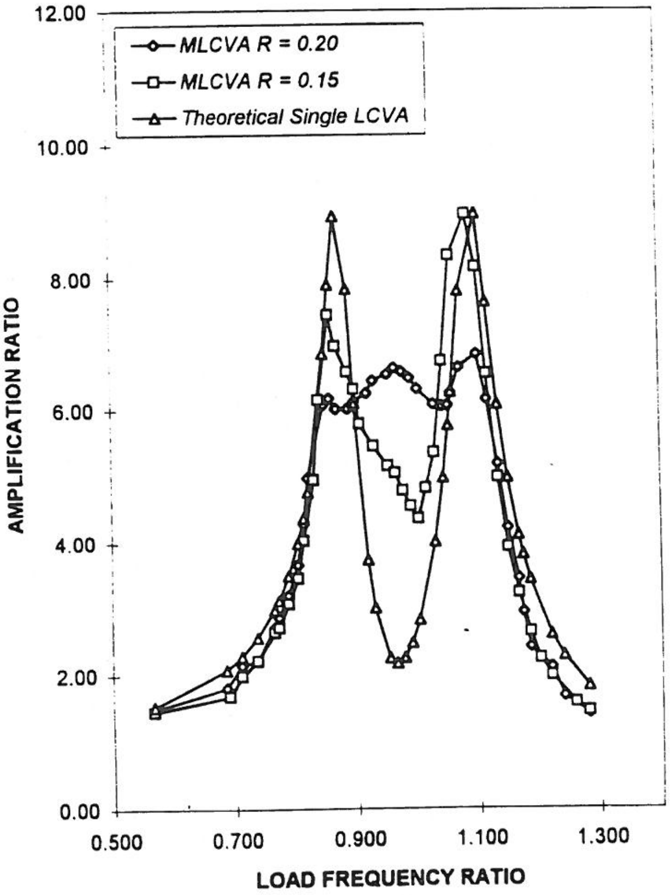

Figure 9. Frequency Band Effects