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VIBRATION RESPONSE OF A FOOTBRIDGE DUE TO PEDESTRIANS' MOVEMENTS

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Failure of footbridges in England and France due to excessive vibrations from marching soldiers in the nineteenth century resulted in many fatalities and injuries. The unexpected lateral vibrations of the Millennium Bridge over the Thames River in London was a watershed event as large number of research studies were conducted on this subject following this incidence. However, there are still a number of issues related to vibration serviceability of footbridges that require further studies. Among these are: the amplification of structural response when a group of pedestrians cross a footbridge as compared to a single individual (group effects). This is important as footbridge vibrations are usually computed when subjected to one pedestrian's crossing and are magnified to estimate those generated by a group of people. Therefore, it is important to conduct vibration testing of footbridges to better define the group effects. This paper presents an experimental study of a footbridge susceptible to vibrations due to human movements. With the help of a group of volunteers, the group effects were computed as a function of the group size. It was found that the results were not completely consistent with those in the literature. Conclusions are made based on the results of the data analysis.

Keywords: Footbridge vibration, Group effects, Vibration serviceability, Enhancement factor, Human-structure interactions.

1 INTRODUCTION

Footbridges can be susceptible to large vibrations due to human movements. The excessive vibrations of the Millennium footbridge over the Thames River in London (Dallard *et al.* 2001) initiated large number of research studies focused on evaluating the vibration serviceability issues of footbridges.

To evaluate the dynamic response of footbridges, the structural designer needs to have a good estimate of the applied loads. It is customary to compute the response of a footbridge subjected to a single pedestrian, and increase the results when a group of people moves over the structure. Therefore, few researchers have studied the vibration amplification when a group of pedestrians cross a footbridge as compared to that due to an individual. This amplification is represented by the "enhancement factor".

Matsumoto *et al.* (1978) proposed an enhancement factor of $\sqrt{N}$ to estimate the vibration amplitude of a footbridge when crossed by a group of N pedestrians from that attributed to one person, assuming a Poisson arrival probability distribution. Wheeler (1982), Bachmann and Ammann (1987), and Barker (2007) conducted analytical studies to define the enhancement factors. Unfortunately, all conducted investigations on this subject consisted of analytical studies with very limited experimental verifications.

Setareh (2016, 2017) conducted studies on the group effects in footbridges, which are to the knowledge of the authors the only experimental investigation conducted on this topic. Setareh (2016) conducted a number of dynamic tests with a group of human subjects and concluded that when the pedestrians walked slowly or at normal speed in unison, the enhancement factor for group effects increased approximately by the square root of the group size as proposed in the literature for the random walks. However, when the group speed approached the first mode natural frequency of the footbridge, the enhancement factor became closer to the group size.

Setareh (2017) conducted an experimental study of another footbridge and concluded that when people moving in unison on a footbridge at the structure's fundamental frequency, the enhancement factor is significantly larger than the recommended values in the literature. He also observed that the enhancement factors for when the people move in unison at the footbridge fundamental frequency is close to the number of people for smaller group size. This reduces with an increase in group size, which can be attributed to an increase in the footbridge damping due to human-structure dynamic interactions and the fact that it is more difficult for a larger group to move in unison.

To add to the available literature on this issue, this paper presents an experimental study of the group effects on a footbridge using a number of human subjects. It uses different evaluation parameters and computes the enhancement factors. It provides the results of the data analysis and concludes on the outcome.

2 DESCRIPTION OF THE STRUCTURE

The footbridge used in the study connects a multi-story building to an adjacent parking structure located in Blacksburg, Virginia (see Figure 1). It is made of a steel structure consisting of two trusses at 8 ft apart with a standard Pratt configuration. The total length of the footbridge is 116'-10" and has a clear depth of 7'-6". All the truss members are made of Hollow Structure Shapes (HSS), which are welded together. The top chord is made of HSS6x6x3/8, the bottom chord consists of HSS8x6x3/8, the verticals are HSS6x6x3/8 and the diagonals are made of HSS4x3x1/4. The truss panel points are 9'-0" apart. The footbridge floor deck consists of a 20 gage, 2-inch thick form metal deck with 4 inches of concrete topping (total thickness=6"). The concrete has a compressive strength of 3,500 psi.

Figure 1. Footbridge used in the study.

3 DESCRIPTION OF THE TESTS

To measure the resonance frequency of the structure, an electrodynamic shaker was placed on the footbridge and the frequency response function (FRF) was found. This resulted in a resonance (natural) frequency for the vertical modes of 4.08 Hz and 11.43 Hz.

Subsequently, up to 32 volunteers participated in a series of walk tests on the footbridge. Four speeds were selected: (1) 122 spm (steps per minute) to represent the half-harmonic of the measured first vertical mode natural frequency, (2) 110 and 115 spm to investigate the possibility of reduction in the structure's natural frequency due to the presence of pedestrians; and (3) random movements. PCB 393C accelerometers were placed at the center of the footbridge on both sides to record the vibrations along the three orthogonal directions. However, since the largest vibrations occurred in the vertical direction, this study will focus on these measurements only.

Using a metronome to synchronize their movements, different groups of volunteers (1, 4, 8, 14, 20, 26 and 32 people) crossed the footbridge from one end to another and stopped while the measurements were completed. Figure 2 shows a group of pedestrians crossing the footbridge during one of the tests. An OROS signal analyzer was used to record and analyze the data.

Figure 2. People walking on the footbridge during the test.

4 GROUP EFFECT STUDIES

Different vibration evaluation parameters were computed for the measurements made during the conducted tests. These include the peak acceleration (a_p), maximum transient vibration value (MTVV) and vibration dose value (VDV). For detailed definition of these parameters, please refer to Setareh (2017). For computing the values of the MTVV and VDV, the frequency weighting function, W_k, from the International Standard ISO2631-1 (1997) was used.

The enhancement factors for a_p, MTVV and VDV for different groups of pedestrians were computed by dividing the values for each group by its counterpart for an individual pedestrian. To provide more consistent values and minimize the effects of noise and biases during the tests, each data point was computed by averaging the values from two accelerometers on the two sides of the footbridge. In addition, each test was conducted twice, once the volunteers crossed the footbridge from left to right and again from right to left. The results for these tests were also averaged for each step frequency. Therefore, the results used for the analysis were based on the average of four data sets.

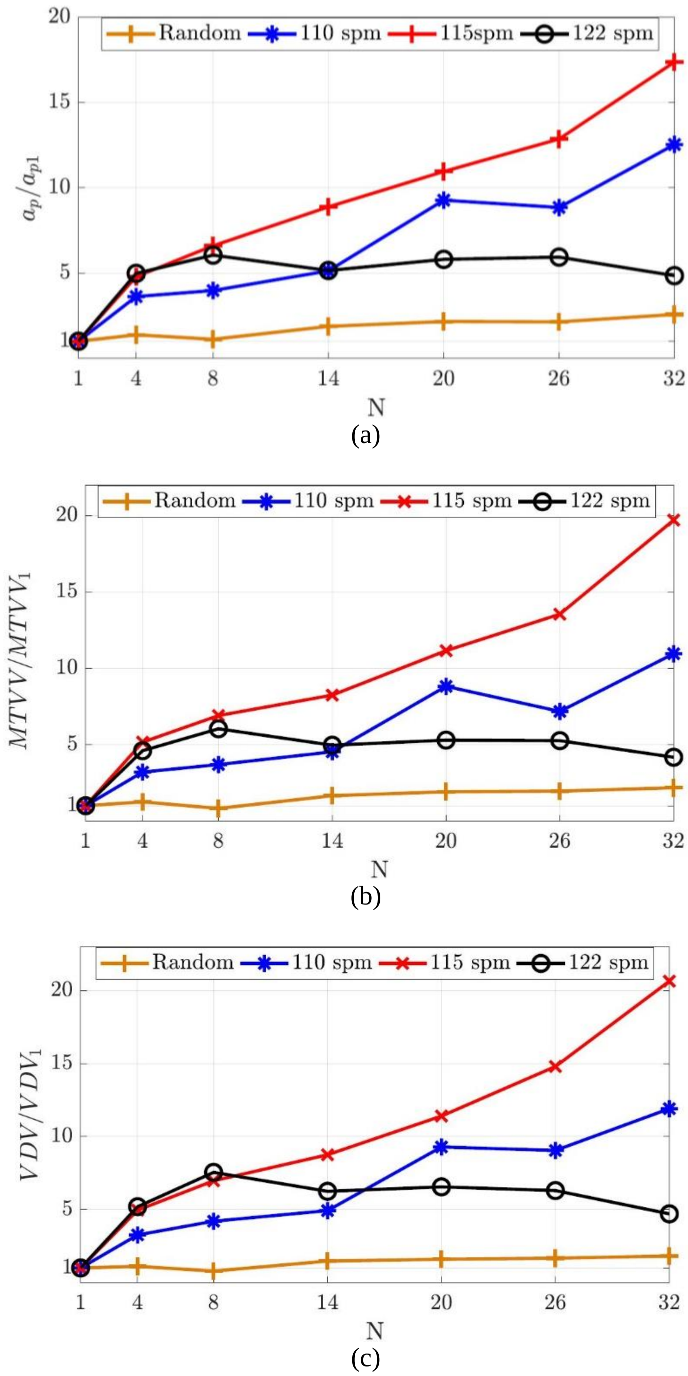
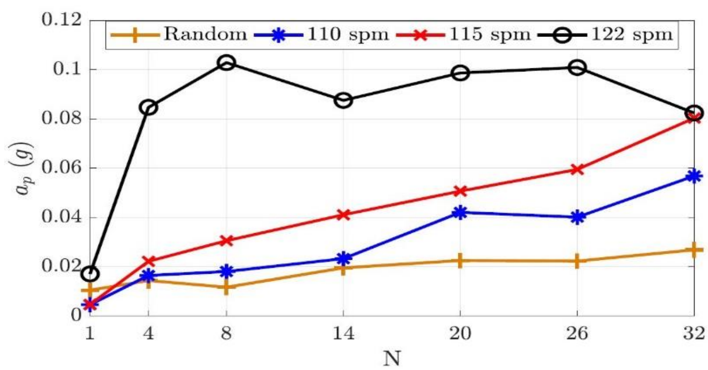


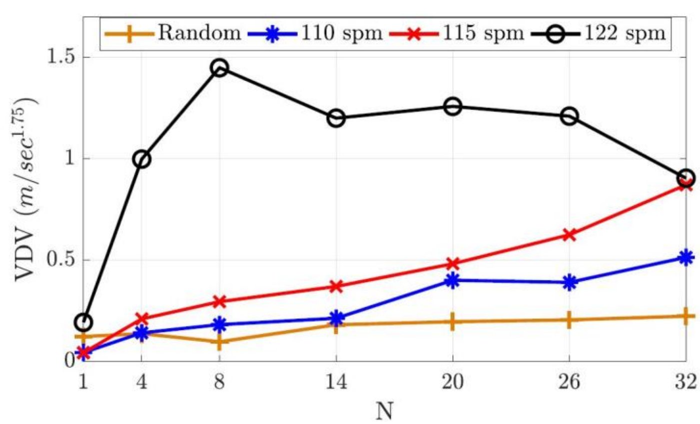
Figure 3. Variation of different group enhancement factors with group size (N):
(a) a_p/a_{p1} vs. N; (b) MTVV/ $MTVV_1$ vs. N; (c) VDV/VDV_1 vs. N.

Figure 3 shows the enhancement factors for different evaluation parameters versus the number of pedestrians for different step frequencies. As expected, the enhancement factors for the random walks are small. However, the unexpected observation is the reduction of these values when more than eight pedestrians walked at the sub-harmonic of the natural frequency of the footbridge (122 spm) even though for the 110 and 115 spm the enhancement factors increased with an increase in the number of people.

To better comprehend the results, the peak acceleration and VDV versus the number of people for each walk speed is shown in Figure 4. As can be observed, the peak acceleration and VDV for the case when the pedestrian moved at the sub-harmonic of the natural frequency were much larger than when they walked at other speeds. This may have resulted in some of the pedestrians not being able to keep their pace with the beat from the metronome. However, the results from the prior studies conducted by Setareh (2017) show that at the measured vibration levels this could not cause the level of reduction in the footbridge response observed here.



(a)



(b)

Figure 4. Peak acceleration and VDV values for different group size and various walking speeds: (a) a_p vs. N; (b) VDV vs. N.

The other major factor in reducing the enhancement factor, when the people walked at 122 spm, can be attributed to the effects of human-structure interactions. Based on the measured dynamic properties of the footbridge, if the natural frequencies of pedestrians were close to the vertical mode of vibration, they could act as tuned mass dampers (TMD), absorbing the vibration energy, and result in a reduction in footbridge response. As the mass ratio between the pedestrians and the footbridge increases (with more pedestrians), the required equivalent TMD damping ratio increases. Since human body has inherently large damping levels, as the number of people increases the human bodies become more tuned to the structure and result in larger vibration reduction. This can provide an explanation of the observed phenomenon. More studies are needed to provide a quantitative evaluation of the effects of the observed human-structure interactions.

5 CONCLUSIONS

This paper provided the results of studies conducted on a footbridge to evaluate the group effects. The presented results show a reduction in the enhancement factors when a number of pedestrians (beyond a limit) walked at the sub-harmonic of the footbridge natural frequency. This was attributed mainly to the effects of human-structure interaction and to a lesser degree to the inability of the pedestrians to keep pace with each other when the footbridge had large levels of vibration.

Acknowledgments

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