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A Study of Human Reaction to Building Vibrations Due to Occupants' Movements

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Abstract

Excessive vibrations in building structures due to occupants' movements such as walking have become prevalent. This is mainly due to the use of higher strength construction materials, long-span column-free architectural designs, and use of equipment highly sensitive to small levels of vibrations such as MRI machines and electron microscopes. Therefore, it is important that the building designers use reliable vibration limits for the level of acceptable vibrations to humans. Current standards and design guides in the U.S. limit the vibration levels based on peak or root-mean-squared (r.m.s.) of acceleration. Past research studies have shown that these parameters do not provide reliable means for the evaluation of building vibrations. A more reliable vibration evaluation criterion, called "Vibration Dose Value" or VDV, has been introduced and recommended for use by the International Standardization Organization and the British Standards. It has been shown that VDV provides consistent results in terms of the assessment of human reaction to vibrations generated by mechanical equipment. However, currently there is not any reliable VDV limits for building vibrations due to people movements. Therefore, this paper presents a research study to establish relationships between VDV and other vibration parameters to come up with limits for acceptable levels of VDV. It attempts to answer the following research questions: 1. Can VDV be related to other vibration parameters such as peak acceleration ($a_{w,p}$) or the maximum one-second running root-mean-squared of acceleration (MTVV) to establish limits on acceptable building vibrations to humans?, and 2. Can such limits be reliable and verified against subjective measurements? Vibration testing and measurements on three large commercial buildings were conducted. Using the collected data, relationships between various vibration evaluation parameters (VDV, $a_{w,p}$, and MTVV) have been established. Frequency-weighting functions from four different international and British standards were used. Using the relationships developed between the parameters and the documented limits for $a_{w.p}$ and MTVV, new limits for VDV were recommended. These limits were then compared to the typical values recommended in the literature for other applications. In addition, subjective reactions of the building occupants participated in this study have been collected. They were then compared to the suggested limits in this study. From this study it was found that consistent relationships between VDV and $a_{w,p}$, and VDV and MTVV do exist. The comparison of the limits with the subjective evaluations showed that the VDV limits for acceptable vibrations suggested in this study can be used for the assessment of building vibrations due to human movements. The results presented here can be used by engineers and architects to more reliably assess building vibrations due to human movements.

Keywords: Building Vibrations, Vibration Assessments, Vibration Dose Value

1. Introduction

Excessive vibrations due to occupants' movements have become prevalent. The main reason for this is the use of high strength construction materials and long-span column free designs. It is very important to use reliable vibration limits for the level of acceptable vibrations for humans.

Currently there are three parameters that can be used to assess building vibrations. These parameters include Vibration Dose Value (VDV), Maximum Transient Vibration Value (MTVV), and Peak Acceleration ($a_{w,p}$). The ATC-03 used in the U.S. and the National Building Code of Canada recommend the use of peak acceleration.[1] [2] However, the peak acceleration is susceptible to errors due to variations in signal processing parameters such as filtering. MTVV is defined as the "maximum transient vibration value," which basically represents the maximum one-second running root-mean-squared (r.m.s.) of vibration.[3] VDV was introduced more recently and studies have shown it to be more accurate than other parameters.[4] Unlike peak acceleration, which averages vibration effects, VDV accumulates vibration effects and is a better evaluation parameter.[4] In the following equation, T is the exposure duration and $a_w(t)$ is the frequency-weighted acceleration.

$$VDV = \left[\int_{t=0}^{t=T} a_w^4(t)\,dt \right]^{1/4} \tag{1}$$

VDV increases as vibrations prolong. Currently, VDV has no reliable limits for office building vibrations due to human movement. Therefore, this study tries to establish a relationship between VDV and other vibration parameters, including MTVV, and $a_{w,p}$ to propose acceptable limits of VDV.

2. Vibration Testing

The first step of this study involved vibration testing that took place at three different Virginia Tech buildings. Each building was tested twice: once while the building was under construction, and once when the building was near completion. These vibration tests involved a series of walk tests. On both test events the exact same walk tests were performed, except different walking frequencies were used since the natural frequencies of floors changed. For these walk tests an accelerometer was placed on the floor to measure vibrations. Accelerometers measure acceleration at the point at which they are placed. Multiple accelerometers were used at various locations of the floor, and were placed at the center of the bay in order to measure the largest floor response. The accelerometers were connected to a signal analyzer, which was connected to a computer that collected the raw acceleration data. The three buildings tested were the Academic and Student Affairs Building (ASAB), the Infectious Disease and Research Facility (IDRF), and the Visitor and Undergraduate Admission Center (VUAC).

2.1 Academic and Student Affairs Building (ASAB)

The first set of tests were done in April 2010 when the building was under construction. The April 2010 tests were conducted along two wings of the building. For the first wing of the building the walking frequencies were 120 steps per minute (spm), 125 spm, and 154 spm. All the walk tests were synchronized using a metronome. The second set of walk tests was done along the other wing of the building, and the walking frequencies were 120 spm, 126 spm, and 140 spm. The exact same tests were performed again in April 2012 when the building was near completion. The walking frequencies used for the first wing were 128 spm, 148 spm, and 120 spm and the walking frequencies used for the second wing were 108 spm, 158 spm, and 120 spm. The natural frequencies of floors changed due to the addition of non-structural elements.

Figure 1. ASAB during and after construction condition

2.2 Infectious Disease and Research Facility (IDRF)

The first set of walk tests were conducted when the building was under construction in February 2011. There was a slab on the second floor where the testing occurred but no stud walls were in place. Mechanical and plumbing equipment were installed as well. The tests were performed along the future corridor of the building at 120 spm, 146 spm, and 155 spm. The second set of walk tests were conducted when the building was near completion in October 2011. At the time of the testing, suspended ceilings were in place as well as mechanical and electrical equipment, however furniture was not present. The exact same walk tests were performed as February 2011 tests, however the walking frequencies used were 120 spm, 144 spm, and 161 spm.

Figure 2. IDRF during and after construction conditions

2.3 Visitor and Undergraduate Admissions Center (VUAC)

The first tests were conducted in October 2011 when the building was under construction. At the time of testing, stud walls were in place around the perimeter of the structure. The walking frequencies were 120 spm, 118 spm, 127 spm, 134 spm, and 147 spm. The second set of walk tests were performed in May 2011 when the building was near completion. At the time of the testing, occupancy was expected within six weeks. All mechanical and electrical systems were in place, as well as some carpeting. The exact same walk tests were performed, but at different frequencies. The walking frequencies used were 120 spm, 137 spm, 146 spm, and 158 spm.

Figure 3. VUAC during and after construction conditions

3. Data Analysis

Once the raw data was collected from each accelerometer, they were processed with MATLAB software in order to calculate VDV, $a_{w,p}$, and MTVV. Four different weighting functions W_k[4], W_b[5], W_g[5], and W_m[6], were used to compute the vibration parameters. These weighting functions are multiplied by the Fast Fourier Transform (FFT) to modify the measured vibrations to reflect human sensitivity, since the body is more sensitive within specific ranges of frequencies. Figures 4 to 6 show VDV plotted against both $a_{w,p}$, and MTVV for each building using different frequency weighting functions. These plots include all of the data across both testing days. A first order curve was also fit through the entire data for each building.

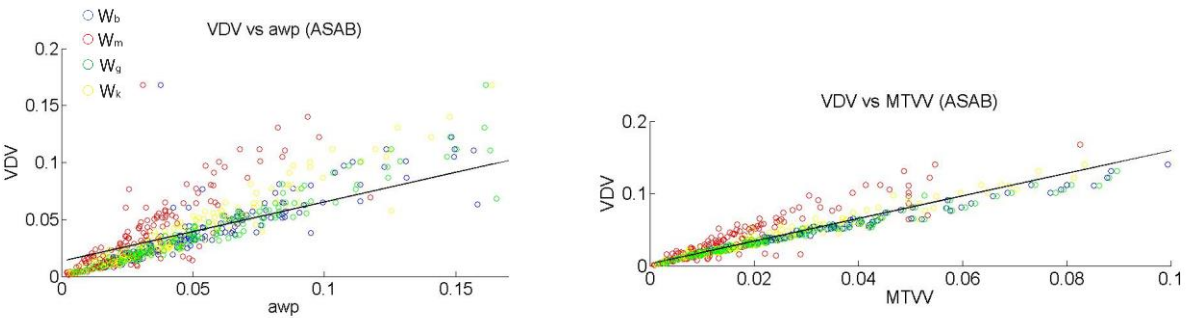

Figure 4. ASAB scatter plots

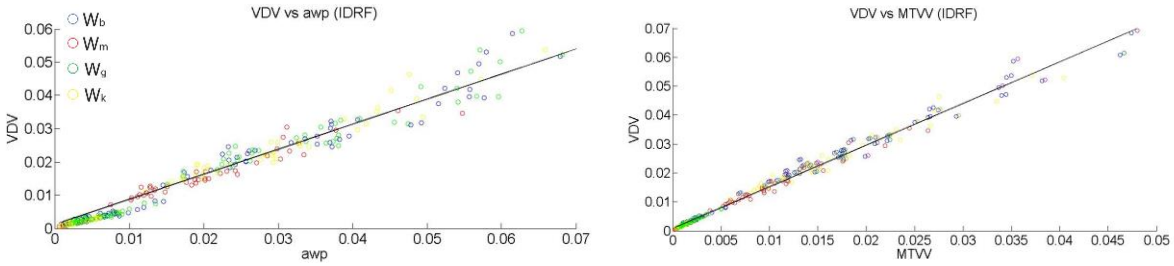

Figure 5. IDRF scatter plots

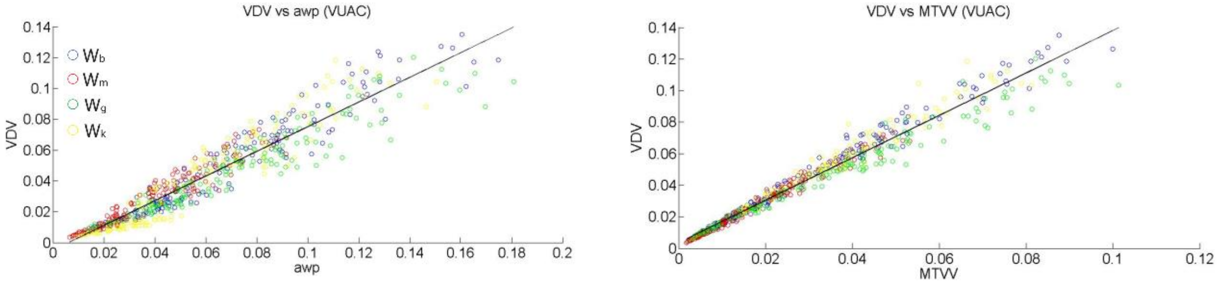

Figure 6. VUAC scatter plots

The above plots were analyzed to determine R^2 (goodness of fit) values and the slope of the line of best fit to determine a relationship between VDV vs. $a_{w,p}$ and VDV vs. MTVV. R^2 shows the strength of the relationship between the data being compared. A value close to 1 is ideal, while a value of 0 indicates no relationship. The resulting R^2 values are shown in tables 1 and 2. Based on the higher R^2 value of VDV vs. MTVV, it can be concluded that there is a stronger relationship between VDV and MTVV.

Table 1. VDV vs. $a_{w,p}$ (R^2 Value)

Building	W_b	W_m	W_g	W_k
ASAB (April 2011)	0.9427	0.9587	0.9707	0.945
ASAB (April 2012)	0.9872	0.988	0.9886	0.9907
IDRF (February 2011)	0.9225	0.9265	0.9289	0.9151
IDRF (October 2011)	0.8932	0.9447	0.9311	0.9034
VUAC (October 2010)	0.9213	0.8805	0.8986	0.9205
VUAC (May 2011)	0.8679	0.8268	0.8258	0.8249
Average R^2 Value = 0.9212				

Table 2. VDV vs. MTVV (R^2 Value)

Building	W_b	W_m	W_g	W_k
ASAB (April 2011)	0.9791	0.935	0.9755	0.9799
ASAB (April 2012)	0.992	0.9915	0.9867	0.9933
IDRF (February 2011)	0.9712	0.9696	0.9689	0.971
IDRF (October 2011)	0.9681	0.9693	0.9711	0.9704
VUAC (October 2010)	0.9618	0.9467	0.9555	0.9603
VUAC (May 2011)	0.9586	0.9578	0.9358	0.9278
Average R^2 Value = 0.9665				

4. VDV vs. $a_{w,p}$ and MTVV Relationships

In order to recommend acceptable VDV limits for floor vibrations, two methods were used. The first is establishing a relationship between VDV and $a_{w,p}$, and the second method is establishing a relationship between VDV and MTVV.

4.1 Estimation based on relationship with $a_{w,p}$

A best-fit line was generated for each plot. The slope of the best-fit line was determined in order to establish a relationship between VDV and $a_{w,p}$. The average A_1 value for VDV vs $a_{w,p}$ is A_1=0.65, where A_1 is the slope of the best-fine line. The data is shown in table 3.

$$VDV = A_1 * a_{w,p}$$
$$VDV = 0.65 * a_{w,p} \quad (2)$$

Table 3. VDV vs. $a_{w,p}$ (A_1 Value)

Building	W_b	W_m	W_g	W_k
ASAB (April 2011)	0.8522	1.4	0.95555	0.8443
ASAB (April 2012)	0.4558	0.5701	0.4913	0.4647
IDRF (February 2011)	0.7279	0.673	0.7099	0.7172
IDRF (October 2011)	0.4729	0.5061	0.5003	0.4932
VUAC (October 2010)	0.5254	0.4828	0.3325	0.5033
VUAC (May 2011)	0.7815	0.7677	0.7980	0.6613
Average A Value = 0.65				

4.2 Estimation based on relationship with MTVV

The same estimation method was used to determine a relationship between VDV and MTVV. The average slope of the line of best fit for the VDV vs. MTVV plot is 1.43, where A_2 represents the slope of the line of best fit. The data is shown in table 4.

$$VDV = A_2 * MTVV$$
$$VDV = 1.43 * MTVV \quad (3)$$

Table 4. VDV vs. MTVV (A_2 Value)

Building	W_b	W_m	W_g	W_k
ASAB (April 2011)	1.457	2.085	1.5282	1.4321
ASAB (April 2012)	1.7494	1.3821	1.7063	1.6882
IDRF (February 2011)	1.3373	1.3287	1.3213	1.3384
IDRF (October 2011)	1.3985	1.4230	1.4256	1.4091
VUAC (October 2010)	1.3281	1.263	1.2634	1.3024
VUAC (May 2011)	1.3541	1.3405	1.3819	1.1586
Average A Value = 1.43				

5. Estimating VDV Limits

Table 2 shows the R^2 (goodness of fit) values for each VDV vs. MTVV plot. Since the average R^2 values for VDV vs. MTVV is higher than VDV vs. $a_{w,p}$, it can be concluded that there is a stronger relationship between VDV and MTVV. Because the A values for VDV vs. MTVV are more consistent and the R^2 values are higher, it can be concluded that there is stronger relationship between VDV and MTVV. For this reason, the relationship between VDV and MTVV will be used in order to come up with a reliable limit for VDV.

Using the lowest acceleration r.m.s of 0.005 m/sec2 and multiplier 8 based on Smith, et al.[7], the allowable limit for one walk event is MTVV ≤ 0.04 m/sec^2. Based on the average A value for VDV vs MTVV, it can be concluded that VDV=1.43 x MTVV. However, for the purpose of this study, it can be rounded to:

$$VDV = 1.45 \times MTVV \quad (4)$$

Allowable VDV for one walk event:
Acceptable MTVV limit = MTVV ≤ 0.04 m/sec^2

$$\begin{aligned} &VDV = 1.45 \times MTVV \\ &VDV = (1.45 \times 0.04) = 0.058 \\ &VDV \leq 0.058 \text{ m/sec}^{1.75} \end{aligned} \tag{5}$$

6. Subjective Evaluations

The second part of the study involved comparing the collected data to subjective evaluations. Surveys were conducted at each tested building, and employees of the buildings were asked to rate the vibrations they felt based on the following scale:

1 = not perceptible
2 = somewhat perceptible
3 = perceptible
4 = somewhat perceptible
5 = uncomfortable
6 = somewhat annoying
7 = annoying

Occupants indicated perceptible vibrations were felt near the stairs of the ASAB building. These vibrations were mainly felt when large crowds entered the building. Occupants did not notice any vibrations in the IDRF building. Occupants indicated that only somewhat perceptible vibrations were felt near the conference room at the VUAC building.

7. Conclusions

The focus of this study was to establish a relationship between different vibration evaluation parameters in order to determine a reliable limit for the Vibration Dose Value (VDV). Through the use of vibration testing that was performed on three Virginia Tech buildings, a relationship between VDV and MTVV was shown to be the most reliable comparison in order to come up with a reliable VDV limit, which was determined to be VDV ≤ 0.058 m/sec$^{1.75}$. Based on the collected data the Academic and Student Affairs Building had the most vibrations. This was consistent with the subjective analysis. This building had VDV values that reached as high as 0.4, which is well over the VDV limit of 0.058 m/sec$^{1.75}$ determined in this study. This is consistent with the subjective evaluation of the employees, who expressed high, perceptible vibrations in the building. However, most of the occupants indicated that most vibrations were felt near the stairs, but this was not necessarily supported by the collected data from the testing. This could be attributed to the fact that during working hours large crowds use the stairs, which would increase floor vibrations, however these conditions were not present during the time of testing. The employees of the Infectious Disease and Research Facility indicated that there were no vibrations in the building. This was consistent with the testing that was done, because this was the only building of the three where all VDV measurements, after construction, were under 0.058 m/sec$^{1.75}$. At completion of the construction, the Visitor and Undergraduate Admissions Center had some vibrations that were higher than the proposed limit of 0.058 m/sec$^{1.75}$. Even though some occupants had complaints about a particular location near the conference room having vibrations, the data did not show significantly higher VDVs for this location. Through the study it was also determined that vibrations were higher among all buildings when the building was under construction. This is most likely because there were no partition walls and damping when the tests were conducted during the construction that would have minimized any vibrations. It can be concluded that by comparing VDV to MTVV, a reliable VDV limit can be proposed. The testing also shows that partition walls and other finishing materials help to minimize building vibrations.

8. Acknowledgments

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