A Portable Real Time Data Acquisition System for the Comparison of Floor Vibration Data with AISC Design Guide 11 Estimates

Authors:
Matthew D. Dodge, Graduate R.A., Tufts University, Dept. of Civil & Env. Engineering
Masoud Sanayei, Professor, Tufts University Department of Civil & Env. Engineering
Eric M. Hines, Associate, LeMessurier Consultants; Research Assistant Professor, Tufts.

ABSTRACT

A portable real time vibration measurement data acquisition system was assembled with the intention of studying the accuracy of the results provided by the AISC Design Guide 11 [Murray, Allen and Ungar] design equations. Some experiments were conducted in the field with the interest of refining experimental methods and obtaining preliminary data. Some observations were made regarding the data obtained in these experiments.

THEORETICAL BACKGROUND

In response to the increasing incidence of vibration problems in modern floor systems, research into the parameters affecting the vibrational behavior of these floor systems has been ongoing since the 1950’s. The most recent document to become available to structural engineers for designing floor systems to avoid vibration problems is “Floor Vibrations due to Human Activity”, number 11 in AISC’s Design Guide Series. This document provides engineers with a method for designing floor systems to prevent floor vibration problems with respect to human comfort arising from the transient excitation imparted by the walking of human subjects and the harmonic excitation resulting from crowds engaging in rhythmic activities. It also provides a method that can be used to design floor systems to prevent vibration problems relative to the operation of sensitive equipment arising from walking excitation.

All of the design equations provided within Design Guide 11 are based on the assumption that a floor system’s behavior can be idealized as that of a single degree of freedom (SDOF) oscillator with an effective natural frequency, an effective damping ratio, and an effective mass. Classically derived equations can then be used with an experimentally determined damping ratio and user estimated values relating to the stiffness of the floor system to predict the response of a floor to an experimentally determined forcing function. This response is then compared to criteria that have also been determined experimentally in order to determine the acceptability of a floor design.

The method presented in Design Guide 11 for estimating the first natural frequency of a floor system can be most simply portrayed as assuming that the beam and girder sizes for a floor system can be taken as typical throughout the system and calculating one natural frequency each for a typical beam and a typical girder using the formula
\[ f_n = \frac{\pi}{2} \sqrt{\frac{gE_t I_t}{WL^4}} \]  

where \( g \) is the acceleration due to gravity, \( E_t \) is the elastic modulus of steel, \( I_t \) is the transformed moment of inertia of the composite member section, \( w \) is the total expected distributed load on the member, and \( L \) is the length of the member. Composite action is assumed in all cases where members are in contact with the floor deck, not just where the member is designed as composite relative to strength criteria.

The beam and girder natural frequencies are then combined using Dunkerley’s relationship [Thomson and Daleh 358-360]:

\[ \frac{1}{f_n^2} = \frac{1}{f_j^2} + \frac{1}{f_g^2} \]  

where \( f_n \) is the combined (system) natural frequency, \( f_j \) is the joist or beam natural frequency, and \( f_g \) is the girder natural frequency.

The equation used to establish the acceptability of a floor system relative to human comfort criteria when subjected to walking excitation is as follows:

\[ \frac{a_p}{g} = \frac{P_o \exp(-0.35f_n)}{\beta W} \leq \frac{a_o}{g} \]  

where \( a_p \) is the expected peak acceleration, \( P_o \) is the maximum expected force, \( \beta \) is the modal damping ratio, \( W \) is the effective weight of the system, and \( a_o \) is the maximum allowable acceleration. This criterion is designed to be sensitive to damping since humans have been shown to be more sensitive to vibrations that persist for more than 5 cycles [Lenzen 134].

The equation used to project the acceptability of a floor system relative to human comfort criteria when subjected to rhythmic excitation is as follows:

\[ f_n \geq (f_n)_{req'd} = f \sqrt{1 + \frac{k}{a_o/g} \frac{\alpha_i W_p}{w_t}} \]  

where \( f_n \) is the first natural frequency of the floor system, \( (f_n)_{req'd} \) is the minimum natural frequency required to prevent resonance, \( f \) is the forcing frequency being designed for, \( k \) is an experimentally determined constant for the type of activity expected, \( \alpha_i \) is the dynamic coefficient associated with the \( i \)th harmonic of the forcing function, \( W_p \) is the effective weight per unit area of the activity participants, and \( w_t \) is the effective total weight per unit area of the floor system and the activity participants. This criterion presumes that the vibration amplitude associated with a condition of resonance would be unacceptable and requires that the natural frequency of the floor system be high enough to prevent resonance from occurring.

The equation used to predict the acceptability of a floor system to ensure the satisfactory operation of sensitive equipment when subjected to walking excitation is as follows:

\[ \frac{\Delta_p}{f_n} \leq \frac{V}{U_v} \]  

where \( \Delta_p \) is the displacement of the floor system under a 1 kN concentrated load, \( V \) is the maximum velocity of vibration that can be tolerated by the equipment being designed for, and
where $F_m$ is the maximum force resulting from a single footstep based on the expected occupant weight and walking speed, and $f_o$ is the inverse of the time it takes for the load from a footstep to increase from zero to $F_m$. Parameters $F_m$ and $f_o$ have been determined experimentally and are available in tabulated form in Design Guide 11. The sensitive equipment criterion (5) does not account for damping because the floor system must be designed for a peak, rather than sustained, value of velocity. This is due to the fact that a measurement or manufacturing process that would be disturbed by the threshold value $V$ would only need to be exceeded instantaneously for the effects to result in an unacceptable condition.

**EQUIPMENT AND SOFTWARE**

In the summer of 2004, the Civil Engineering Department of Tufts University began the assembly of a portable system that could be used to excite floor systems with automated forcing functions, measure floor vibration amplitudes on several channels simultaneously, and provide real time access to vibration data in the field. It was intended that this system would then be used to measure the parameters predicted using the Design Guide 11 equations in buildings that were either in construction or in service in order to evaluate the accuracy of those design equations. This system could also be used to evaluate a number of modal parameters for many different “real world” floor systems with the hope of eventually building a large enough body of data so that trends could be recognized that would aid in the refinement of these methods.

At the time that this system was assembled, Tufts already had an electrodynamic shaker in its possession. This unit, an APS Dynamics Electro-Seis Model 400, is capable of applying dynamic forces of up to seventy pounds in its present configuration and can be used to excite frequencies from two to 250 Hertz. In order to measure floor vibration amplitudes, a number of Wilcoxon Model 731A seismic accelerometers were acquired. These accelerometers were selected because of their high sensitivity and ability to sense very low frequency vibrations. A Wilcoxon Model 799M accelerometer was acquired for monitoring the accelerations of the shaker’s armature, the moving part of the shaker that is used to apply forces to the systems being studied. This accelerometer was selected for this function because, like the floor accelerometers, it is capable of measuring very low frequencies, but has a sensitivity that is more appropriate for the high accelerations expected at the shaker armature. In order to digitize and record acceleration data, as well as to control the shaker, a National Instruments DAQPad 6052-E external data acquisition unit was acquired. This unit is capable of digitizing eight differential channels of acceleration data in separate voltage ranges with a resolution of 16 bits at scan rates of up to 333,000 scans per second, and communicates with a laptop computer via a Firewire connection.

In order to control the data acquisition and the shaker, a suite of programs called “Virtual Instruments”, or “VI’s”, was written in National Instruments’ LabView graphical programming language. There are currently five different kinds of VI’s within the suite. The first VI records time history data on several channels simultaneously for the purpose of calculating averaged amplitude spectra. The second VI allows the user to control the frequency and amplitude of the shaker’s harmonic excitation and observe time
history data and amplitude spectra of several channels in real time. The third VI controls an automated sine sweep test, using user specified parameters, that refers the vibration amplitudes from several accelerometers to the shaker excitation and calculates the averaged transfer function magnitudes and phases for each accelerometer location. The fourth VI uses the shaker to apply a harmonic excitation to a floor system at a resonant frequency, abruptly stops the shaker, and calculates the floor’s damping ratio from the logarithmic decrement of the resulting floor vibrations. The fifth VI continuously monitors floor vibration amplitudes on several channels and starts recording once a user specified threshold has been exceeded. These five VIs and the equipment have been used successfully at a number of sites. The data collected at these sites has been consolidated for presentation in this paper and compared to predictions made using the Design Guide Equations.

**EXPERIMENTAL DATA FROM A CONVENTION CENTER MEETING ROOM**

One of the locations visited was a convention center meeting room referred to as location 305. This location was chosen for the presentation of sample data because it represents a location that is very similar to the idealized, regular framing assumed by the Design Guide calculation procedures. The floor slab in this location is comprised of 4½” of normal weight concrete on 3” thick composite deck, for a total thickness of 7½”. The girders are 60 foot long W36x210 steel sections and the beams are 30 foot long W21x44 steel sections spaced at 10 feet on center. All of the beams and girders are simply supported.

**Ambient Vibration Recording Test**

The first test performed in this location, as in most locations, was an ambient vibration recording test. This test was performed to establish a “baseline” for the comparison of other test data by establishing the levels of vibrations present in the floor system prior to the application of test related excitation. A plot of the measured time history data from this test showed an overall peak ambient vibration velocity of 0.04 mm/s (1570 µin./s) for comparison with walking test time history data, and acceleration spectral peaks of approximately 25x10⁻⁶ g at 4.8 and 9 Hz for comparison with heel drop data.

**Heel Drop or Impact Testing**

One of the tests performed at this location was a heel drop test. This test was performed with an accelerometer set up in the middle of the bay. A researcher performed a heel drop while the data acquisition system was recording. Figure 7 illustrates a plot of the amplitude spectrum from this test resulting in several peaks. It is observed that the first peak, visible at 3.9 Hertz, is the smallest of the peaks. The largest peak is observed at 9.0 Hertz. This suggests that the response of this system, which is as close to the idealized floor system used for the Design Guide 11 equations as possible, will probably respond to walking excitation in a more complex manner than that of a SDOF oscillator.
Walking Induced Vibration Recording

Another type of test conducted at this location was a walking test from one end of the meeting room to the other end and back. Figure 8 shows a time history plot of the data recorded in a walking test conducted at 100 steps per minute.
Walking tests were conducted at 80 to 100 steps per minute. It was intended to conduct the slower of the two walking tests at 50 steps per minute, but there was no means of synchronizing the walking cadence with a calibrated source at the time of the test, so the walking speeds actually varied. The researcher applying the walking excitation for this test weighed 170 pounds. Figure 8 shows that a peak velocity of 0.36 mm/s (14200 µin/s) was encountered in the course of this test.

**Sine Sweep Testing**

A sine sweep test was also conducted at this location. The shaker was used to excite harmonically a continuously changing frequency from 3 Hertz up to 25 Hertz. This test revealed that resonances were actually occurring at all of the peaks observed in the amplitude spectrum graph calculated previously. The existence of these resonance frequencies was confirmed by the presence of shifts in the transfer function phase data occurring at the same frequencies as the peaks in the transfer function magnitude graph shown in Figure 9 and the heel drop amplitude spectrum shown in Figure 7.

![Figure 9](image_url)

**FIGURE 9**
TRANSFER FUNCTION MAGNITUDES FROM A SINE SWEEP TEST IN A CONVENTION CENTER MEETING ROOM

**Damping Ratio Testing**

Another test performed at this location was a logarithmic decrement damping ratio test. In this case, however, the test was conducted at 5.3 Hertz, the third natural frequency of the floor system due to confusion at the time of the test regarding the value of the first natural frequency. In spite of this, the test data can suffice as a demonstration of the kind of data resulting from such a test. Figure 10 shows the time history data from this test.
FIGURE 10
TIME HISTORY OF A DAMPING RATIO TEST IN A CONVENTION CENTER MEETING ROOM AT THE THIRD NATURAL FREQUENCY

FIGURE 11
TRANSFER FUNCTION MAGNITUDE PLOT USED TO CALCULATE THE DAMPING RATIO IN A CONVENTION CENTER MEETING ROOM AT THE FIRST NATURAL FREQUENCY

Another means of calculating the damping ratio is to use the half power method on a transfer function magnitude plot. An example of this for the first natural frequency of this floor system can be seen in Figure 11. The half power method was used as an alternate
method of calculating the damping ratio for the first mode of every floor system that was tested using the logarithmic decrement method and good correlation was seen between the results obtained using the two methods. Because of this previous success of both methods, the 3% damping ratio calculated in Figure 11 seems reasonable.

**SUMMARY OF ALL MEASURED DATA AND DESIGN GUIDE 11 CALCULATIONS**

Table 1 shows all of the data that was obtained for floors with “regular” framing plans. In order for a framing plan to be considered regular for the purpose of this research both girders must be the same size and length, and floor beams must also be the same size and length, with similar boundary conditions. Every floor system studied in the course of this research was framed on wide flange structural steel sections, with the only exceptions being the university classroom, which is a reinforced concrete system, and the outdoor footbridge, which uses two sets of welded trusses using rectangular hollow structural steel shapes for its main members. Tables 1, 2, and 3 compare design values (from Design Guide 11) and measured values for each of the structures investigated. Structures are identified by function and primary structural bay size.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Convention Ctr. Loc. 10a 60’x60’ Ballroom</th>
<th>Convention Ctr. Loc. 305 30’x60’ Mtg. Rm.</th>
<th>University Classroom 15’x31’</th>
<th>Average Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted $f_n$ (Hz)</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>13</td>
</tr>
<tr>
<td>Measured $f_n$ (Hz)</td>
<td>4.8</td>
<td>3.8</td>
<td>3.8</td>
<td>16</td>
</tr>
<tr>
<td>% Difference $f_n$</td>
<td>-29</td>
<td>-13</td>
<td>-22</td>
<td>-21</td>
</tr>
<tr>
<td>Predicted $\beta$ (%)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Measured $\beta$ (%)</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>% Difference $\beta$</td>
<td>-33</td>
<td>-33</td>
<td>-50</td>
<td>-39</td>
</tr>
<tr>
<td>Predicted $v_{80}$ (mm/s)</td>
<td>N/A</td>
<td>0.30</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Measured $v_{80}$ (mm/s)</td>
<td>N/A</td>
<td>0.33</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>% Difference $v_{80}$</td>
<td>N/A</td>
<td>-9.1</td>
<td>N/A</td>
<td>-9.1</td>
</tr>
<tr>
<td>Predicted $v_{100}$ (mm/s)</td>
<td>N/A</td>
<td>0.96</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Measured $v_{100}$ (mm/s)</td>
<td>N/A</td>
<td>0.33</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>% Difference $v_{100}$</td>
<td>N/A</td>
<td>167</td>
<td>N/A</td>
<td>167</td>
</tr>
</tbody>
</table>

**TABLE 1**

**COMPARISON OF MEASURED VS. PREDICTED VIBRATION DATA FOR REGULAR FLOOR SYSTEMS**

It can be seen from the data presented in Table 1 that the Design Guide 11 calculations are reasonably accurate and generally conservative, with a slightly unconservative value occurring for the 80 step per minute walking test. The one value in this table that stands out as being inaccurate is the calculated velocity value for the 100 step per minute walking test, where the peak velocity measured was the same as that for the 80 step per minute walking test. The values predicted by the Design Guide 11 equations for peak velocities in response to walking excitation were calculated using the actual walking speeds and subject weights used in the experiments so as to provide comparable results.
### TABLE 2
**COMPARISON OF MEASURED VS. PREDICTED DATA FOR PEDESTRIAN BRIDGES**

Table 2 shows all of the data that was obtained for footbridges in the course of this research. It can be seen from this data that the calculated footbridge natural frequencies were fairly accurate and somewhat conservative. The measured damping ratios for the two indoor bridges are much higher than the calculated values. The measured damping ratio for the outdoor footbridge was slightly lower than the calculated value, but very close. The outdoor footbridge has deep welded steel trusses for its primary members supporting a composite deck located at the bottom chord level. The two indoor bridges are more similar in construction to ordinary steel composite floor systems, and had more non-structural materials in place, including glass railings and wooden scaffolding.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Convention Ctr. Footbridge BwA 30’ Span</th>
<th>University Lab Footbridge 4-2 42’ Span</th>
<th>University Outdoor Footbridge 72’ Span</th>
<th>Abs. Average Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted $f_n$ (Hz)</td>
<td>7.5</td>
<td>8.8</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Measured $f_n$ (Hz)</td>
<td>8.6</td>
<td>8.7</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>% Difference</td>
<td>-13</td>
<td>1.1</td>
<td>-20</td>
<td>11.4</td>
</tr>
<tr>
<td>Predicted $\beta$ (%)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Measured $\beta$ (%)</td>
<td>4</td>
<td>4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>% Difference</td>
<td>-75</td>
<td>-75</td>
<td>100</td>
<td>83</td>
</tr>
</tbody>
</table>

### TABLE 3
**COMPARISON OF MEASURED VS. PREDICTED VALUES FOR IRREGULAR FLOOR SYSTEMS**

Table 3 shows all of the data that was obtained for irregular floor systems in the course of this research. The common irregularity for these locations was that the girders had...
different sizes and/or spans. The predicted values shown in this table were calculated using the procedures from Design Guide 11, with the only exception being an alteration made to the calculation procedure for the girder mode natural frequency. The girder mode natural frequency was calculated in these locations by averaging the values of $\Delta g$ for the two girders in each location and calculating $f_g$ based on that value. Design Guide 11 does not have a provision to account for this type of irregularity, and it seems likely that a design engineer would use this approach when calculating the fundamental natural frequency for such a floor system. It has been observed that provisions were not made for such irregularities because such a floor will not exhibit the kind of resonant behavior that is likely to annoy building occupants [Adams and Murray 9-10], but in some cases floors with this kind of irregularity still must be checked for acceptability with regard to sensitive equipment criteria. It is apparent from the results of tests that are summarized in Table 3 that for irregular floor systems Design Guide 11 procedures are not very accurate and result in very conservative results.

**SUMMARY AND CONCLUSIONS**

Several floor systems have been investigated to date with the Tufts University Portable Real Time Data Acquisition System, and so far it has yielded some insight into the accuracy and applicability of the equations used to predict the values of these parameters. Observations made using this system using the limited data in tables 1, 2, and 3 indicate that the equations provided in Design Guide 11 for calculating the fundamental natural frequency and peak velocities due to walking at different speeds are generally accurate and when in error are usually conservative. It was also observed that indoor footbridges with finish materials such as glass railing systems may be much better damped than previously thought due to energy absorptions by the glass railings and other finish materials. Fundamental natural frequencies of irregular floor systems cannot be accurately predicted using the provisions of Design Guide 11 even by using what might appear to be a logical means of “extending” those provisions.

The Tufts University Portable Real Time Floor Vibration Data Acquisition System has become an effective, powerful, and convenient means of measuring floor vibration parameters. Future research performed using this system is likely to expand the body of knowledge available for enhancing presently available design methods.

**REFERENCES**


