Chapter 1
Introduction and Literature Review

1.1 Introduction

In recent years, floor vibration due to human activity has become widely recognized by structural design engineers in North America as an important limit state for steel-framed floor systems. While in decades past, design engineers focused their attention exclusively on strength and deflection serviceability limit states, it is now common to evaluate floor vibrations for most, if not all, projects constructed using steel-framed systems. The publication of the AISC Design Guide Series 11, Floor Vibrations Due to Human Activity (Murray et al. 1997, hereafter referred to as “DG11”) provided engineers with evaluation criteria for several common situations and also served to enhance awareness of the importance of routinely considering this limit state.

When needing to perform a floor vibration evaluation, North American design engineers can turn to DG11 for most situations. The evaluation methods in DG11 are based on single degree of freedom (SDOF) approximations and are sometimes difficult to apply to cases for which the criteria are not directly applicable. For these specialized cases, design engineers can attempt to use more elaborate evaluation methods from other sources, the most prominent being the British SCI Design of Floors for Vibration: A New Approach which contains a “General Assessment for Establishing Vibration Response” using the finite element method (Smith et al. 2007, hereafter referred to as “SCI DG”). This method attempts to quantify the response considering multiple modes. It is the experience of the writer and other researchers that finite element programs cannot predict multiple modes at the correct frequency spacing and with mode shapes in the correct order. The method also depends on an indirect formulation: determine the response to steady-state walking and then reduce this response to account for imperfect resonant build-up.

Therefore, the objective of this study is to develop relatively simple vibration evaluation methods that are directly applicable to a wide range of situations and can be practically implemented by structural design engineers. Enhanced understanding of
response to walking and the variables affecting the quality of prediction is also a very important goal.

For this study, the scope is limited to low frequency steel-framed floors and walking excitation. Three methods are presented. Each is intended to use readily available finite element software that can be found in many structural design offices. In the first method, the evaluation is performed by creating a finite element model of the floor, determining natural frequencies, applying individual footstep forcing functions at resonant frequencies, generating a predicted acceleration waveform, and comparing the waveform to a tolerance criterion. It uses concepts that are familiar to engineers who are not vibration specialists. For example, the method uses response history (time history) analysis which will be much more intuitive to a non-specialist than a frequency domain method. Also, footstep forces are applied to the model at approximate footstep locations, an option much faster and easier for non-specialists to understand than Fourier series terms applied at the bay center to represent a walker moving across the bay. The proposed method should be easily adapted for high frequency floors by selecting representative footsteps that cause specific impulse responses.

Response history analysis using Fourier series loading is also presented as an alternative, perhaps more convenient, method. In summary, a finite element model is developed as described in the previous paragraph, but the human footstep forces are modeled using a Fourier series applied at midspan. Response history analysis is used to predict the acceleration due to walking. This method has the advantage of being easier to apply in some analysis programs. It is also similar to traditional methods of predicting floor vibration response, but includes modifications based on this research.

Finally, a simplified frequency domain method is also presented and proposed to be the most convenient overall method for design office usage. A finite element model is developed as previously described. The accelerance FRF magnitude (acceleration response and force both at midspan of the bay under consideration) is computed by the analysis program using steady-state analysis and then used to predict the single mode response to one harmonic of the Fourier series representing human walking.

Three laboratory specimens, one full-scale mockup, and two building floors were vibration tested to obtain measured natural frequencies, mode shapes, critical damping
ratios, steady-state acceleration response, and acceleration responses due to walking excitation. The results of these tests are used to judge the accuracy of the proposed response prediction methods.

This dissertation is organized as follows: The remainder of Chapter 1 is a literature review of relevant papers and design guides. Chapter 2 describes the experimental methods used during the research, including detailed discussions of issues associated with structure-shaker interaction and walking acceleration test post-processing. It also contains a description of footstep force measurements and post-processing. Chapter 3 describes the analytical methods used to generate predictions for comparison with the experimental results. Chapter 4 contains a documentation of the comparisons of experimental results to analytical predictions. Chapter 5 contains proposed prediction methods which are based on the comparisons of measurements and predictions. Chapter 6 contains a discussion of sensitivity and probability considerations. Finally, Chapter 7 contains conclusions, recommendations for future research, and a discussion of the use of probabilistic methods for floor vibration evaluation.

1.2 Literature Review

The body of literature dedicated to floor vibration serviceability is vast at this point in history and includes subjects as diverse as human perception to vibration, experimental modal analysis of structures, finite element modeling of structures, footbridge lateral vibration, passive and active control, sensitive equipment, and footstep loading functions. Numerous theses, dissertations, and papers have been written on these, and other floor vibrations topics by structural engineers, mechanical engineers, and biomedical engineers.

The purpose of this literature review is not to cover each and every floor vibration topic, but to review the literature relevant to the research objective, that is to develop finite element modeling procedures for predicting floor vibration response to walking excitation. Therefore, it is necessary to review and summarize the current guidance available to structural engineers needing to check floor vibrations. Literature containing comparisons of experimental results with predictions by the current design guides is reviewed to set basic expectations for the accuracy of the proposed method. Several researchers have compared experimental results to finite element predictions. This
review focuses on experimental programs that included modal tests conducted with measured forces and those including walking tests. The proposed method will require information regarding human footstep forces and their application to structures. Therefore, literature regarding force waveforms and their application is reviewed. Finally, very recently, probabilistic procedures have been proposed. The current state of these procedures is discussed briefly (see Chapter 6 also).

1.2.1 Current Guidance for Floor Vibration Serviceability

Currently, structural engineers have two main sources of guidance with regard to floor vibration serviceability: DG11 and the SCI DG. The guidance contained in these design guides is summarized in this section.

**AISC Design Guide Series 11: Vibration Due to Human Activity**

The AISC Design Guide Series 11: Vibration Due to Human Activity is the de facto standard in North America and is summarized here; for extensive commentaries, see Avci (2005) and Barrett (2006). The underlying background of DG11 is found in the paper by Allen and Murray (1993). DG11 contains three criteria: “Design for Walking Excitation,” “Design for Rhythmic Excitation,” and “Design for Sensitive Equipment.” The first criterion is the one of interest for the proposed research. It centers around prediction of the bay’s fundamental frequency and steady-state peak acceleration response and is applicable to a very wide range of situations faced by structural design engineers. The fundamental frequency is predicted by combining the beam natural frequency and girder natural frequency, both determined using classical vibration theory and the Dunkerley equation. The peak acceleration is predicted using a single degree of freedom approximation (SDOF) of the bay under consideration. The loading function is an approximation of a four term Fourier series that represents the frequency content of the force due to walking. The effective weight of the equivalent SDOF system is computed using equations derived from orthotropic plate theory, as influenced by building dimension limitations. Load and response are presumably at mid-bay (an antinode in the presumed mode shape), although DG11 states that response elsewhere may be approximated using the predicted fundamental mode shape.
DG11 provides guidance relevant to the proposed research, including the dynamic elastic modulus of concrete, effective slab width for transformed section calculations, design damping ratios, and a reasonable step frequency range (1.6 Hz to 2.2 Hz).

**SCI Design of Floors for Vibration: A New Approach**

The SCI design guide, *Design of Floors for Vibration: A New Approach* contains current British guidance for the evaluation of floor vibrations. Two broad approaches are presented: a finite element analysis procedure entitled “General Assessment of Establishing Vibration Response” and a procedure suitable for manual calculations, entitled “Simplified Assessment for Steel Floors.” The former is based on the procedure proposed by Willford et al. (2006), discussed elsewhere in this section. The latter is similar to the DG11 approach in that it centers around estimating the fundamental frequency and acceleration response of the floor due to walking. The fundamental frequency is estimated as the lowest of the “Secondary Beam Mode” and “Primary Beam Mode” fundamental frequencies. The secondary beam mode frequency is computed assuming that the secondary beams are simply supported, slab ends are fixed, and the girder is rigid. The primary beam mode is computed assuming that the primary beams are pinned and that the secondary beams and slab ends are fixed. This has been shown to be more accurate than the DG11 frequency prediction procedure (Hicks 2004, Murray and Boice 2004, Davis and Murray 2007b). The acceleration response is quantified as the RMS acceleration. Similar to DG11, it is computed using the solution derived for an equivalent SDOF system. The effective mass is computed using orthotropic plate theory and limited by building dimensions. The acceleration prediction equation includes mode shape amplitudes at the load and response and a resonant build-up factor which depends on the walking path length and walking speed, among other variables.

The SCI DG “General Assessment of Establishing Vibration Response” is an adaptation of the method proposed by Young (2001) and Willford et al. (2006). They presented a general frequency domain vibration serviceability criterion suitable for use with a finite element program. The researchers present a comparison of their proposed method (and several other methods) with measured results, indicating that their method is more accurate than the other established methods for those particular cases. For low frequency floors, the steady state acceleration responses are computed and combined on a
mode by mode basis. In the writer’s opinion, while it might be more accurate than other current methods, it is more complex than necessary considering the current ability to predict modal properties using finite element analysis. Of primary interest toward the proposed research goal is their forcing function determination. They used a very large number of measured footstep waveforms obtained from various researchers to determine Fourier components of walking forces. Due to the enormous variability in footstep forces, they selected design values for the first four harmonics of the walking force corresponding to a 25% probability of exceedance. Their method also requires computing response due to multiple modes. It is the writer’s experience, and that of Pavic et al. (2007) that models created using the best current engineering judgment are not capable of reliably predicting multiple modes in the correct order and at the correct frequency spacing. There is also some question as to whether multiple modes must be considered (Ellingwood and Tallin 1984, Ellis 2000). The results reported by Davis and Murray (2007b) also indicate that the maximum acceleration response was achieved due to excitation of a single mode, although not always the fundamental mode.

1.2.2 Comparisons of Experimental Results with Predictions by Current Procedures

Several researchers have reported comparisons of experimental results with response predictions generated through the use of the current procedures. These papers are summarized in this section.

Sladki (1999) compared measured natural frequencies and peak accelerations for numerous buildings with DG11 predictions. He concluded that the frequency predictions were reliable, but that the peak acceleration predictions were not.

Hicks (2004) presented a historical overview of floor vibrations criteria and then described the (then) currently used SCI Design Guide on the Vibration of Floors (Wyatt 1989) and DG11 design guide criteria. He discussed floor vibration tests and then presented comparisons of measurements and design guide predictions for eight floors. He reported that both design guides accurately predicted natural frequencies, but conservatively predicted acceleration response in most cases. For the low frequency floors tested, both design guides predicted accelerations approximately 30% on the conservative side, but with very large coefficients of variation. Hicks also compared the experimental results with the Willford et al. (2006) finite element modeling procedure.
with a very good average ratio of test to prediction (0.98), but with a very high coefficient of variation (57%). Several finite element modeling predictions were very far on the conservative side, but some were very far on the unconservative side. Hicks reports the wide data dispersion even though measured damping values were used in the response predictions. This indicates the difficulty of response prediction, perhaps attributed to the enormous variability in footstep forces.

Murray and Boice (2004) compared predictions using four procedures (Modified Reiher-Meister Method (See Murray and Boice (2004) for a description), Murray Criterion, DG11 Chapter 4, and the SCI 1989 procedure) to occupant subjective evaluations for 51 bays in 32 buildings. They concluded that the DG11 procedure was the most accurate of the three methods and was in very good (88%) compliance with occupant observations of adequacy.

Davis and Murray (2007b) presented comparisons of modal and walking test results with predictions based on the DG11 Chapter 4 criterion and the SCI DG simplified vibration evaluation criterion. A total of five bays were tested in two buildings, one built using composite slabs supported by hot-rolled steel beams and the other built using a non-composite slab supported by open-web steel joists. The researchers reported that the design guide procedures under-predicted the natural frequency. DG11 unconservatively predicted the peak acceleration due to walking by an average of approximately 20% whereas the SCI DG procedure was conservative by approximately 40% on the average. One outlying measurement was excluded from the averages. The response of the bay with the outlying measurement was very inaccurately predicted by both design guides, presumably due to restraint conditions not considered by the simplified models used in the design guides.

1.2.3 Modal Tests and Comparisons with Finite Element Models

Several researchers have reported studies which include modal tests of building floors. A few of these included finite element modeling predictions and a few others included walking tests. Numerous other papers include the results of footbridge tests and laboratory specimens, but many of these are of limited scope and use unreferenced (force measurements not recorded) measurements, so are of limited relevance toward the
proposed research objective. The following reviewed papers are limited to include only steel framed buildings.

The research performed by Khoncarly (1997) is the most similar to the proposed research because it contains one of the only instances found in the literature of combined modal tests, walking tests, and finite element model predictions. The objective of his research was “to develop practical design guidelines, in the form of smoothed response spectra, for use in the design and evaluation of typical office floor systems excited by one individual walking at reasonable pacing frequency.” Toward this goal, the researcher measured the walking force waveform generated by three individuals using an instrumented force plate. Limited modal tests and walking tests were then performed in one bay of an occupied steel-joist supported building floor system with reported vibration problems. One natural frequency was measured using unreferenced heeldrop tests. Walking tests were performed at a “brisk pace” using one of the individuals with previously measured footstep waveforms. It is unclear how the walking frequency was selected, although it was estimated from viewing the floor acceleration waveform troughs. A finite element model of the floor was created and used to predict natural frequencies, with good agreement with test results. Walking was modeled by applying a spatially varying footstep force at arrival times matching the model’s natural frequency second subharmonic. The results were extrapolated to create an evaluation procedure centering around response spectra, but the time domain finite element modeling is of primary interest for the proposed research. The agreement of the model with modal and walking test results is very positive, although several aspects of the reported research leave doubts as to its repeatability, in the writer’s opinion. First is the walking frequency, 167 bpm (2.78 Hz), which was estimated from observation of the measured waveform. The researcher observed the trough times and declared them to be footstep times, which is approximately true in the writer’s experience. While the waveform seems to clearly indicate excitation by a second harmonic at approximately 167 bpm, this walking frequency is very far outside the range of normal walking and perhaps even beyond the capability of most walkers. Numerous other sources list “reasonable” step frequency ranges of approximately 1.6 Hz to 2.2 Hz (DG11, Kerr 1998, Ellis 2000, Pachi and Ji 2005). The SCI DG lists a step frequency range of 1.5 Hz to 2.5 Hz, which was the
widest found in the literature. It is the writer’s opinion that natural, or even hurried, walking over 2.3 Hz (140 bpm) is extremely unlikely, so the tests seem to have limited applicability to practical evaluations. Second, the indirectly measured step frequency second harmonic is 0.4 Hz different from the measured natural frequency whereas the analytical prediction was performed using a step frequency exactly equaling the model’s natural frequency second subharmonic. Third, the analytical prediction also included significant contributions from modes with frequencies as high as 25 Hz, which is well outside the frequency range of interest for floor vibrations.

Sladki (1999) developed a finite element modeling technique using SAP2000 Version 7.1 and successfully verified the classical results obtained for simple models. He compared the measured natural frequencies and peak accelerations due to walking with finite element model predictions for eight buildings. His finite element models were able to predict the natural frequencies with good accuracy, but were not able to predict the peak accelerations. He attributed the large differences to the fact that applied forces were not measured during the tests.

Ellis (2000) used walking test results performed on a full scale steel-framed building floor at the Cardington Large Building Test Facility in the UK as the backdrop for a general discussion of walking acceleration waveforms and frequency content. Numerous walking vibration tests were performed, using step frequencies between 1.7 Hz and 2.4 Hz because normal walking felt awkward outside this range. Single and multiple walkers were used and Ellis concluded that vibration evaluation may be reasonably performed using a single walker. The researcher used floor response to indirectly measure the Fourier coefficients of the walking force and made recommendations for coefficients up to the eighth harmonic. He stated that the response due to only a single harmonic is required for floor vibration evaluation. Ellis proposed a peak acceleration prediction method based on a single walker walking at a subharmonic of the natural frequency. His method was compared to test results recorded in a single bay of the Cardington steel building, indicating that it over-predicted the peak acceleration by about 50% if all modes are considered and by about 100% if the measured results were filtered to only include one mode. He attributed the over-
prediction to imperfect resonant buildup during the test and an upper-bound Fourier
coefficient used in the prediction.

Alvis (2001) compared measurements from several specimens, including a
composite joist floor system, to finite element predictions. He indicated that the lower
frequency modes could be successfully predicted by finite element analysis, but that
accelerations could not be accurately predicted. He attributed the differences to
damping—that his SAP2000 (unknown version) models only considered viscous
damping whereas other forms of damping exist in the lab specimen. He also noted that
the measured damping was approximately double the DG11 recommended value for
floors similar to the specimen.

Barrett (2006) presented the results of extensive modal tests on three bare floors
built using conventional composite slabs supported by composite steel beams. He then
developed finite element models of the floors and investigated the various restraint
conditions in an attempt to explain discrepancies between the measured modal results and
predictions. His finite element models accurately predicted natural frequencies.
Accelerance peak magnitude prediction accuracy varied and depended on whether the
measured damping or an assumed damping ratio was used in the model. Most of his
accelerance peak magnitude predictions were reasonably accurate. Finally, he presented
the initial development of a vibration evaluation criterion using the finite element
method, implemented using software (SAP2000 Version 9 (CSI 2004)) which is readily
available to North American design engineers. His evaluation method involved using the
steady-state analysis feature of a modern structural analysis program to generate
predicted accelerance FRFs with a superimposed tolerance curve based on the DG11
Chapter 4 criterion. This general concept is used in this research to develop the
simplified frequency domain method. The main difference is the walking forces used:
the method presented in this dissertation uses updated harmonic forces with a specific
probability of exceedance.

Pavic et al. (2007) presented the results of modal tests and finite element model
predictions for a fully furnished composite floor system. They performed modal tests
using chirp excitation, resulting in estimates of the system natural frequencies and mode
shapes. A finite element model, created using only information available in the design
documents, predicted the first four natural frequencies within approximately 12%. The reported mode shape plots indicate that the predicted mode shapes did not match the measured mode shapes for the 2\textsuperscript{nd} and 3\textsuperscript{rd} modes. The researchers performed manual model updating and automatic model updating in an attempt to match the model to the test results. The updated model predicted the first four natural frequencies within 6% and appeared to predict generally correct mode shapes. They concluded that a “fairly complex FE model of the floor developed on the basis of best engineering judgment could easily yield natural frequencies which were 10-15\% above or below their measured counterparts. The researchers indicated that beam stiffness adjustments from -20 to +20\% were used during the updating process. They speculated that visible cracks above the main beams were the most likely source of the discrepancy. Notably missing from the paper was any indication of the predicted FRF magnitude, which, in the writer’s opinion, is the most important result of finite element model predictions from a floor vibration perspective.

It is very difficult to find in-situ walking test results in the literature, especially ones with accompanying modal tests and finite element model predictions. Almost all studies used modal testing procedures without accompanying walking tests. Indeed, even the reported modal tests have usually focused entirely on prediction of natural frequencies and mode shapes rather than acceleration response, which, in the writer’s opinion is the most important system characteristic from a floor vibration perspective. For example, consider a hypothetical in-situ vibration test that resulted in a natural frequency and accelerance estimate. When judging a finite element model prediction of this floor, it is much more important that the model reasonably predict the accelerance peak magnitude than precisely predict the frequency. The papers that focus on testing, however, seem to almost completely ignore this, and focus almost entirely on frequency predictions rather than acceleration response predictions, with Barrett (2006) being a notable exception. Numerous tests have been conducted over the years with unreferenced heeldrops to determine the natural frequencies, followed by walking tests. However, it is very difficult to find referenced modal tests accompanied by walking tests.
1.2.4 Footstep Forces and Application

Human footstep waveforms, or profiles, have been studied by numerous researchers around the world. Research projects have been performed toward objectives as diverse as intruder detection (Galbraith and Barton 1970) and detecting the differences in footsteps for medical purposes (Stergiou et al. 2002). This section summarizes several papers that are relevant to the proposed research. Application of footstep forces is equally as important toward the proposed research objective. Therefore, several papers are included that provide insight into parameters such as stride length, step frequency, and number of walkers.

Galbraith and Barton (1970) reported the results from a series of walking force measurements conducted to obtain basic input data as part of a study to improve detection of intruders. Seventy-nine footstep force waveforms were recorded for three subjects, whose weights varied from 115 to 250 lbf, stepping on a force plate placed in a 16 ft long walkway. Step frequency was recorded using several methods including a stopwatch and instrumentation attached to the walkway. Three surface materials were used, ranging from very soft (sand and a rubber pad) to very hard. Walkers wore only socks for some tests and shoes during others. The researchers report that the footstep waveforms were primarily affected by the weight and step frequency and were not greatly affected by the type of footwear and surface. They state that the variation from test to test using the same footwear and surface was as great as the variability between tests with different footwear and surface. The paper includes typical footstep waveforms for two of the walkers.

Ellingwood and Tallin (1984) described several aspects of floor vibrations in general and presented tentative serviceability criteria. Of major interest toward the current research is the authors’ assertion that groups of people walking seldom cause vibration problems unless they are intentionally walking in step. This leads to the conclusion that it is possible to evaluate floor vibration serviceability based on a single walker, which is in partial agreement with the conclusions reached by Ellis (2000) and Ellis (2003). The authors also stated that analysis of several floors indicated that the response is sensitive to the choice of footstep forcing function. They also argued for only
considering acceleration contributed by the fundamental mode because higher frequency vibration damps out more rapidly and human perception is related to vibration duration.

Bachmann and Ammann (1987) recommended vertical and horizontal forces to account for walking and running. They also recommend a method for considering group loading. Bachmann et al. (1995) lists dynamic load factors for diverse loads such as walking, running, jumping, hand clapping, and lateral body swaying.

Rainer et al. (1988) presented the results of walking, running, and jumping tests conducted using an instrumented platform and a response prediction procedure. Pernica presented dynamic load factors for individuals and groups of people (up to 4) walking, running, and jumping, also using an instrumented platform.

Kerr (1998) presented the measured footstep force results for walking on flat floors and stairs. The flat floor measurements are of interest for the proposed research. He reported the results of over 1000 footstep force measurements spanning 40 individuals, in terms of Fourier amplitudes. First harmonic amplitudes (1.6 Hz to 2.2 Hz) followed a consistent, although moderately dispersed, pattern, ranging from approximately 24% (3rd order curve fit value) to approximately 46% of the walker’s static weight. Second, third, and fourth harmonic amplitudes were also shown and have no discernible pattern. He indicated that the second harmonic amplitude is considerably lower than the first and that the third and fourth harmonics are even smaller. Beyond the fourth harmonic, the amplitudes were practically zero. He also presents stride length measurements as a function of step frequency and height. Kerr and Bishop (2001) also present results from the same study.

Ellis (2003) presented the results of group walking tests at the Cardington facility, including groups up to 32 walkers. He concluded that large groups caused greater accelerations than a single walker, but that a fairly large group (around 10) was required to exceed the response of a single idealized walker. The researcher also concluded that “doubling the response determined for an individual would appear to reflect crowd loading for any given usage scenario.” This is in only partial agreement with the conclusions by Ellingwood and Tallin (1984).

Ungar et al. (2004) reviewed vibration criteria for sensitive equipment and presented expressions for floor response due to idealized footfall pulses. Of primary
interest for this research is their choice of footstep forcing function. They use a very simple waveform composed of partial sine waves as the beginning and end, with a flat plateau for the middle. They give parameters to define the waveforms for slow (75 bpm), moderate (100 bpm), and fast (125 bpm) walking. Their proposed waveform is fairly similar in form to the ones presented by others for slow walking, but is very different for fast walking.

Pachi and Ji (2005) presented the results of 800 measurements taken on two footbridges and two shopping center floors. The tests were performed to gather statistical data regarding step frequency, velocity, and stride length. The walkers were not aware that they were being observed. They determined that the average step frequencies for walking on the shopping centers floors and footbridges, respectively, were 2.0 Hz and 1.8 Hz. They also determined that the average stride length was approximately 30 in. for men and 26 in. for women. Their histograms indicate that almost all step frequencies were between 1.7 Hz and 2.2 Hz for walking on the shopping center floor and between 1.6 Hz and 2.0 Hz on the footbridges.

The International Federation for Structural Concrete (2005) provides loading functions, mostly based on Bachmann et al. (1995). It also provides a sizeable discussion of group loading of very low frequency footbridges.

Obata and Miyamori (2006) used a genetic algorithm applied to footbridge test results to identify six parameters that describe a footstep waveform composed of two quarter sine waves and a cosine wave.

ISO 10137 (2007) provides an appendix with dynamic load factors for walking and running, among other types of loads.

Ricciardelli and Pizzimenti (2007) present the results of a sizeable study on lateral walking forces.

Willford et al. (2007) used the footstep harmonic force measurements obtained primarily by Kerr (1998) to determine “Mean” and “Design” (75th Percentile) footstep forces as functions of step frequency. These are used in the current research to determine loading functions. Specifically, individual footsteps are selected to have frequency content approximately equal to the 75th percentile forces presented by Willford et al. (2007). Fourier series amplitudes are also based on these values.
1.2.5 Probabilistic Methods

Brownjohn et al. (2004) developed a frequency domain modeling approach for long flexible structures that accounts for walking imperfection of individuals and crowds. They indicate that the leaking of energy into adjacent frequencies accounts for the reduced measured response compared to finite element predictions. One case study is presented, indicating that for normal walking, the degree of correlation of vertical walking forces among pedestrians approaches zero. One useful conclusion for the current research is that a very large number of normal walkers is required to produce an acceleration larger than that produced by a single resonant walker.

Zivanovic et al. (2007) extended the work of Brownjohn et al. (2004) by introducing the concept of subharmonics of walking forces which occur in the frequency domain halfway between main walking harmonics of the walking force. These occur due to the inevitable difference between left and right footsteps. They developed loading models in the frequency and time domains and a response simulation procedure using 2000 generated force histories.

The writer is not aware of any studies that have been performed on other aspects of probability-based design such as occupant and walker location, individual tolerances to vibration, and material properties.

1.3 Need for the Current Research

Three established deterministic procedures exist for the evaluation of floor vibration serviceability due to walking excitation: DG11 Chapter 4, the SCI DG simplified procedure, and the SCI DG general procedure. The DG11 procedure and the SCI DG simplified procedure provide structural design engineers in North America and England with fairly simple criteria that can be used to evaluate most floor bays. However, they are designed for typical floor framing areas with regular bays and can be difficult to apply to other situations. The two procedures have been shown to usually be conservative (Hicks 2004, Davis and Murray 2007b), although sometimes give inaccurate acceleration predictions for atypical bays (Davis and Murray 2007b). In summary, the DG11 procedure and the SCI DG simplified procedure provide structural design engineers with extremely useful and convenient ways to check the majority of floor bays, but may be of limited usefulness for some cases.
For atypical situations, designers can use the SCI DG general procedure which is based on finite element modeling. It was shown by Hicks (2004) to be more accurate than DG11 and the 1989 SCI procedure (Wyatt 1989), although tremendous data dispersion was present in the comparisons. In the writer’s opinion, the main difficulty in applying the SCI DG general procedure is that it requires a specialization in vibration theory that will not likely be present in the vast majority of structural design offices. It is cast into a very general form intending to account for multiple modes of vibration, significantly increasing the complexity of the procedure and learning curve.

A probabilistic procedure has been developed by Zivanovic et al. (2007). This procedure results in predicted probabilities of vibrations exceeding specific levels. However, the procedure is only available through the use of proprietary software owned by the University of Sheffield. Very limited verification of the accuracy of the procedure has been presented by Zivanovic et al. (2007) using measured modal properties in the predictions. The accuracy of any response prediction, regardless of the elaborateness of the loading function, depends on the accuracy of modal property prediction.

Therefore, it is useful to develop alternative response prediction methods, based on finite element modeling and backed up by modal and walking tests. These will be generally applicable, as easy as possible to learn and use, and available for immediate use by design engineers using readily available structural analysis software. Three separate methods are developed in this research. The primary method is response history analysis to predict the response to temporally and spatially varying individual footsteps. These footsteps are selected to provide a specific loading level in the frequency domain. This method is the least abstract method and is widely applicable. For example, if the likely walking path is thought to only be long enough for a few steps (before turning a corner, for example), then an appropriate number of footsteps can be applied. The second method is similar to the first, in that response history analysis is used. The difference is the loading function: Fourier series at one location. This method is easier to apply than individual footsteps, but it has the limitations of not directly modeling the spatial variation of the load. Finally, the third method is a simplified frequency domain method which assumes that one mode provides the majority of the response. This method is probably the fastest and easiest to use for typical designs. The disadvantage, compared to
the individual footsteps method, is that the steady-state response is predicted and then reduced to account for imperfect resonant build-up, a process that is less direct and less accurate than applying footsteps where and when they will be applied. All three methods are shown in this research to provide reasonably accurate response predictions.