

Human-Structure Interaction in Stadiums: Statistical Analysis of Vibration Comfort Levels Variability

ABDULRAHMAN ALGADI, INAD ALQURASHI
and F. NECATI CATBAS

ABSTRACT

Crowd-induced vibrations in stadiums pose challenges to structural integrity, human comfort, and long-term reliability. This paper presents a methodology that integrates ISO-weighted filtering, modal analysis, and statistical distribution modeling to evaluate vibration variability across three seating zones during a football game. Vertical vibrations are collected in the band, lower student, and upper student sections, which were processed to extract the vibration dose value (VDV). Modal peaks at 2.34 and 4.69 Hz were consistent in sections, with an additional 13.18 Hz mode observed in the band zone. Statistical fitting of Normal, Lognormal, and Weibull distributions to the VDV data yielded exceedance probabilities of 10.9%, 20.5 %, and 29.8 % for the band, lower student, and upper student sections, respectively. These results underscore the notable differences in comfort limits variations under identical game conditions. Future work recommendations are extended to apply the approach to multiple games, investigate causal links between variability and crowd-related factors, and quantify the contribution of each section to general discomfort to inform targeted design and maintenance strategies. The predictive capability of the framework offers a valuable tool for stadium monitoring and design optimization.

Keywords. Human-Structure Interaction, Human-Comfort, Statistical Methods, Crowd-induced Vibrations.

INTRODUCTION

Structural health monitoring (SHM) of stadiums, particularly in relation to human-induced vibrations and perceived comfort, is a critical area of research that contributes public safety and structural integrity. Understanding the dynamic interaction between human vibrations and structural response has become increasingly important in recent

Abdulrahman Algadi, PhD Candidate, Email: Aalgadi@ucf.edu. Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, Florida, 32816, USA. Inad Alqurashi, PhD Candidate, Email: Inad.alqurashi@ucf.edu. Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, Florida, 32816, USA. F. Necati Catbas, Professor, Email: Catbas@ucf.edu. Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, Florida, 32816, USA

years, especially with structures of high crowd densities. Studies have focused on quantifying vibration characteristics, such as amplitude, frequency, and root mean square (RMS) values, and correlating these with human perception thresholds [1, 2]. This approach is typically in accordance with various comfort standards or codes, which often take into account demographic factors such as age and gender, as well as the nature of activities occurring during events [3]. Most existing research employs methods such as field measurements with accelerometers and surveys to collect data on both vibrations and human responses [4, 5]. For example, studies have shown that seated spectators are generally more sensitive to vibrations compared to those actively participating in events such as singing or jumping [1]. In addition, specific characteristics of events, such as synchronized actions or intense crowd participation, have been identified as significant contributors to uncomfortable vibration levels [5]. Thus, studies like [6] explored computer vision to understand these dynamics of crowd coordination and loading and then compared them to current comfort serviceability indices. [7] investigated the dynamic loading of the crowd in temporary stands and found that limits are exceeded more frequently in such settings. As a result, research focused on improving comfort indices and not limiting them to raw data acceleration to a more comprehensive index [8, 9]. [10] recently started investigating data-driven approaches to understand the behavior of the crowd in a specific section to understand the dynamic complexity and improve the design of new stadiums. Although current research effectively tackle comfort limits based on predefined codes and human-induced vibrations, it does not explore the variability of these vibrations for different sections. Understanding these differences allows us to interpret the relative contribution of crowd-related vibrations which can then be used to integrate them for future stadium designs and maintenance plans.

METHODOLOGY

The proposed methodology is described in this section. First, vibration data will be collected using a distributed network of accelerometers installed across multiple stadium sections during various events, along with metadata such as seating type and density, behavior type (e.g. jumping, cheering), game statistics and sensor locations. Before dynamically analyzing the data, preprocessing filtering and windowing is applied. Filtering includes applying frequency-weighting filters specified by [11, 12]. Hamming window is also applied for more precise estimation, where the equation below is used to determine the window size:

$$N_w = \frac{F_s}{\Delta f} \quad (1)$$

Where N_w is the number of samples in the window, F_s is the sampling frequency and Δf is the desired frequency estimation resolution. Hence, a 0.05Hz accuracy was chosen, resulting in 4096 samples per window. Finally, an overlapping of 50% is applied to prevent spectral leakage.

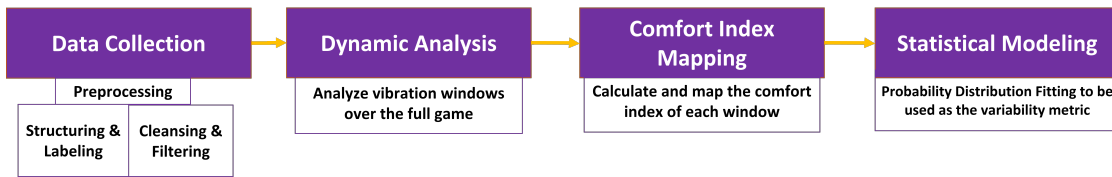


Figure 1. The proposed framework to evaluate the variability of comfort levels in various seating sections

In order to determine whether the structure's behavior has changed over the past years, a dynamic analysis to estimate modal frequencies is performed and compared with historical results. Then for each window, Vibration dose value (VDV) will be computed in accordance with ISO 2631-1. Unlike RMS acceleration, VDV emphasizes higher-magnitude events by raising instantaneous acceleration to the fourth power, thus heavily weighting transient vibrations as the equation below shows:

$$VDV = \left(\int a_w^4(t) dt \right)^{\frac{1}{4}} \quad (2)$$

Incorporating VDV into comfort analysis is essential for scenarios like football stadium events, where sudden crowd activities (e.g., jumping, cheering after goals) significantly influence vibration levels. ISO 2631 define distinct comfort thresholds shown in table I [11, 12]. Finally, statistical modeling will be performed by fitting probability density functions (PDFs) to comfort-related metrics for different seating section. Distributions such as normal, lognormal, and Weibull will be evaluated using fit quality metrics, in this case Mean Squared Error (MSE) to quantify the probability of comfort exceedance under each condition.

TABLE I. Perceived comfort limits for VDV

VDV $\frac{m}{s^{1.75}}$	Human Perception
<0.66	Reasonable for passive person
0.66-2.38	Disturbing
2.38-4.64	Unacceptable
>4.64	Probably causing panic

TEST STRUCTURE AND EXPERIMENTATION SETUP

Figure 2a represent the monitored section of the football stadium of this analysis. Figure 2b shows how the setup was installed showing 24 accelerometers in different elements and sections, 12 sensors in the band section, 5 sensors in the lower student section and 7 in the upper student section. More sensors were installed in the band section since previous reports showed the highest vibrations were induced there.

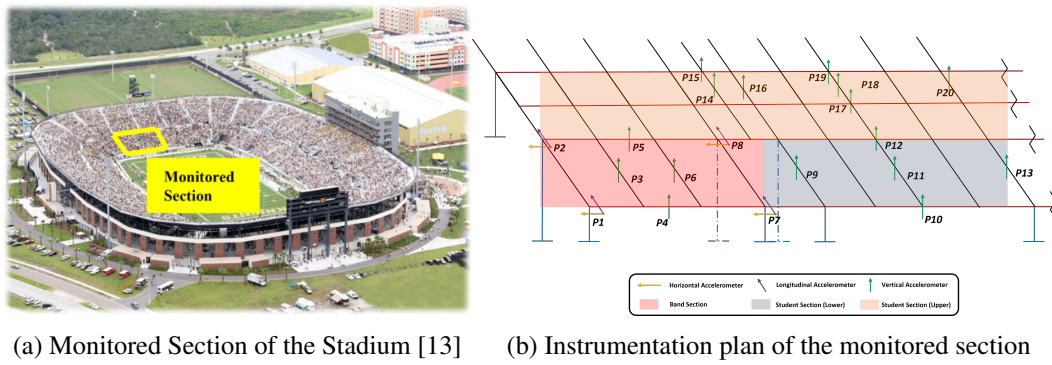


Figure 2. Monitored Section and Instrument Plan

Although multiple datasets were collected for this stadium, only one game was selected to be analyzed to investigate the proposed methodology. Selected dataset represent game number 5 that was played on November 11, 2023. The score was 45-3 in favor of the home team. The duration of the game is 3 hours and 12 minutes (not including pre- and post-game). The weather condition was cloudy, 84F and the game started at 3:35 PM. It is important to note the student sections have high vibrations compared to premium seating, while band are playing music most of the game, and leaving their section to perform during half-time break. Table II summarizes the data attributes that is presented in the following results section.

TABLE II. Preliminary analysis dataset details

Section	Crowd Density	Elements Types	Duration
Student (Lower Segment)	Medium	Stringers, Girders	(4 hours)
Student (Upper Segment)	High	Stringers, Girders	(4 hours)
Band	Medium	Stringers, Girders, Columns	(4 hours)

RESULTS AND DISCUSSION

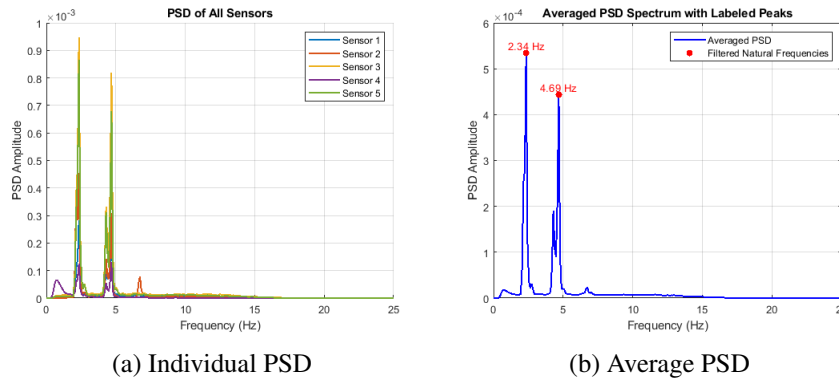


Figure 3. Power Spectral Density response of Upper Segment of Student Section

The result of the dynamic analysis shows similar frequency response from all sections at 2.34 Hz, and 4.69 Hz. However, at 13.2 Hz a peak shows which is not shown in other section indicating another mode in the structure due to band activity. A further investigation is required to determine whether the mode is operational or structural. Table III shows the a summary of the estimated modes while figure 3 shows individual Power Spectral Density (PSD) of each sensor and the averaged PSD values. The estimated values align with previous studies [14] where both 2.34 Hz and 4.69 Hz are found to be the first two operational modes.

TABLE III. Summary of detected modes between 0.5-15 Hz

Section	First Mode (Hz)	Second Mode (Hz)	Third Mode (Hz)
Student (Lower)	2.34	4.69	N/A
Student (Upper)	2.34	4.69	N/A
Band	2.34	4.69	13.18

The figures 4a, 4b, and 4c presented illustrate the VDV indices derived from the vibration analysis performed on stringers in the three distinct seating sections of Game 5. Throughout the entire event duration, frequent exceedance of recommended comfort thresholds are evident across all seating areas. For relative observation comparisons, the Band Section generally experiences relatively lower magnitude vibrations, regularly exceeding the acceptable VDV category threshold of reasonable limits. The Student Lower Section encounters more severe vibration events, frequently surpassing VDV measurements consistently exceed disturbing limits, and often approaching higher limits. The Student Upper Section demonstrates the highest intensity of vibrations among the three analyzed sections with substantial VDV exceedance in unacceptable limits.

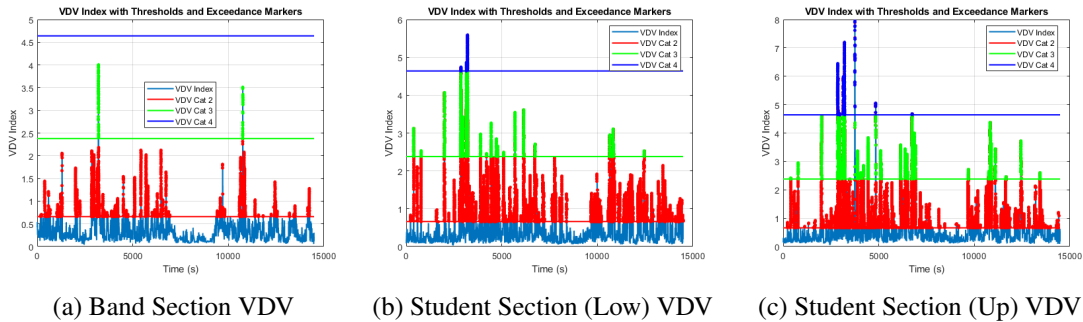


Figure 4. VDV Comfort limits during Game 5 for the selected sections.

Analysis of collected data revealed notable variations in response seating section and crowd activity type. To substantiate and quantify these observations, we employ a consistent analytical window (10 seconds) to calculate comfort levels, which are then modeled using statistical distributions. Subsequently, we calculate the probability of exceeding established comfort thresholds for each factor.

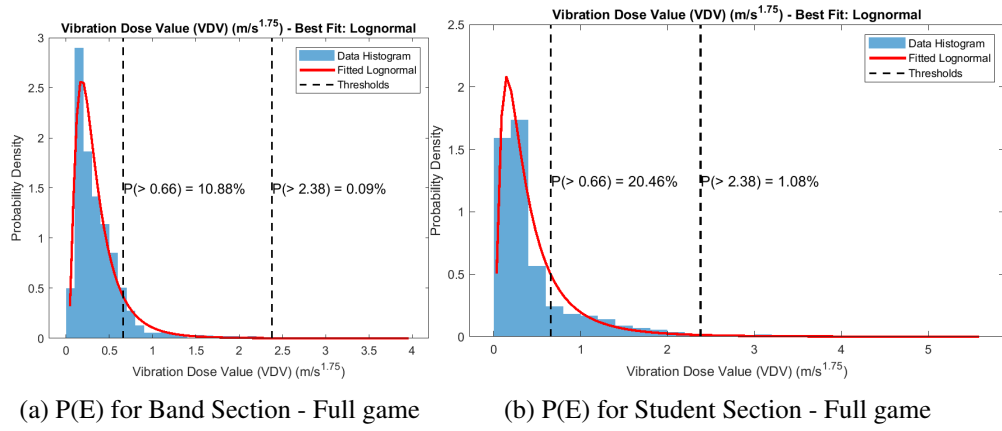


Figure 5. Probability of Exceedance based on crowd type

Figures 5a, and 5b show a sample of the analyzed data, highlighting to distinct crowd types (band and fans). Table IV summarizes the results for the probability of exceeding the disturbing and unacceptable thresholds defined by the vibration dose value index (VDV). For exceeding reasonable limits, notable variations are observed, with probabilities ranging from 10.88% to 29.81%. In contrast, the variations in exceeding acceptable limits are comparatively lower, ranging from 0.09% to 1.45%. These results underscore the significant impact of multiple factors, particularly the type of crowd, crowd density and the structural design of sections.

TABLE IV. Summary of $P(E)$ of Disturbing limits of VDV Index

Section	$P(E)$ Disturbing	Duration	$P(E)$ Unacceptable	Duration
Band Section	10.88%	26 min.	0.09%	13 sec.
Student Section (Low)	20.46%	49 min.	1.08%	144 sec.
Student Section (Up)	29.81%	71.5 min.	1.45%	209 sec.

CONCLUDING REMARKS

This study has demonstrated a data-driven framework for assessing the variability in human-structure interaction in the stadium by combining field measurements, signal processing, and statistical modeling of comfort indices. Applying ISO-weighted filtering and spectral analysis to vibration data from a football game, we reliably captured the first two operational modes at 2.34 and 4.69 Hz in all sections, and discovered a third mode at 13.18 Hz unique to the band section. Comfort mapping through VDV revealed that the upper student section experienced the highest probability of exceeding the comfort limit (29.8%), followed by the lower student section (20.5%) and the band section (10.9%). Fitting multiple distributions to the VDV data for each section produced robust exceedance estimates, highlighting the variability of comfort in vibrations during the same event. These distribution estimates, when generalized, can be used as a benchmark for future development. Future work will extend this methodology to multiple games in successive seasons to reveal long-term trends in vibration variability. Establishing

causal links between measured variability and crowd-related factors such as spectator density, behavior type, and seating type will deepen our understanding of how human activity drives the structural response. Finally, by quantifying the relative contribution of each seating section to the overall comfort limit exceedance, decision makers can then prioritize design enhancements and maintenance interventions in the zones that most critically affect spectator comfort.

REFERENCES

1. G., B., D. A., and W. I. 2008. "Human Perception of Vibrations due to Synchronised Crowd Loading," .
2. Catbas, F. N., M. Gul, and H. O. Sazak. 2011. "Dynamic Testing and Analysis of a Football Stadium," in *Conference Proceedings of the Society for Experimental Mechanics Series*, Springer New York, ISBN 9781441998309, ISSN 2191-5644, pp. 195–203, doi: 10.1007/978-1-4419-9831-6-21.
3. Li, Z., Q. Zhang, F. Fan, and S. Shen. "Analysis of dynamic properties and vibration comfort of large-scale stands," 48(7):802–816, ISSN 0961-3218, 1466-4321, doi: 10.1080/09613218.2019.1693249.
4. A., C., C. A., C. A., and V. M. 2005. "Vibration monitoring of the G. Meazza stadium in Milano during concerts and football matches," .
5. Gul, M. and F. N. Catbas. 2013. "A Review of Structural Health Monitoring of a Football Stadium for Human Comfort and Structural Performance," in *Structures Congress 2013*, American Society of Civil Engineers, pp. 2445–2454, doi:10.1061/9780784412848.213.
6. Turrisi, S., E. Zappa, and A. Cigada. "Vision-Based Method to Measure the Synchronization Level of Jumping Crowds," 72:1–9, ISSN 0018-9456, 1557-9662, doi: 10.1109/TIM.2023.3267536.
7. Lasowicz, N. and R. Jankowski. "Vibration Problems of an Example of Temporary Steel Grandstand under Human-Induced Excitation / Problemy Drgań Przykładowej Tymczasowej Trybuny Stalowej Poddanej Oddziaływaniom Dynamicznym Wywołanym Przez Ludzi," 16(1):119–128, ISSN 2080-5187, 2450-8594, doi:10.1515/ceer-2015-0009.
8. Do, N. T., M. Gül, O. Abdeljaber, and O. Avci. "Novel Framework for Vibration Serviceability Assessment of Stadium Grandstands Considering Durations of Vibrations," 144(2):04017214, ISSN 0733-9445, 1943-541X, doi:10.1061/(ASCE)ST.1943-541X.0001941.
9. Catbas, F. N., O. Celik, O. Avci, O. Abdeljaber, M. Gul, and N. T. Do. "Sensing and Monitoring for Stadium Structures: A Review of Recent Advances and a Forward Look," 3:38, ISSN 2297-3362, doi:10.3389/fbuil.2017.00038.
10. Politecnico di Milano, F. Lucà, SACERTIS Ingegneria S.r.l., S. Turrisi, Politecnico di Milano, E. Zappa, Politecnico di Milano, and A. Cigada. "Exploring Human-Crowd Interaction in Structural Monitoring: Insights from Two Decades of Events at the G. Meazza stadium," 29(7), ISSN 1435-4934, doi:10.58286/29811.
11. 2631-1, I. 1997. "Mechanical vibration and shock-evaluation of human exposure to whole body vibration part 1: general requirements," .
12. 2631-2, I. 2004. "Mechanical vibration and shock-evaluation of human exposure to whole body vibration part 2: vibration in buildings (1 Hz to 80 Hz)," .
13. Celik, O. "Load Estimation, Structural Identification and Human Comfort Assessment of Flexible Structures," .

14. Celik, O., C.-Z. Dong, and F. N. Catbas. 2020. "Computer Vision-Based Human Comfort Assessment of Stadiums," *Journal of Performance of Constructed Facilities*, 34(2):04020005, ISSN 0887-3828, 1943-5509, doi:10.1061/(ASCE)CF.1943-5509.0001345.