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A Method for Multimodal Auralization of Audio-Tactile Stimuli From Acoustic and Structural Measurements

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ABSTRACT

A new method for the reproduction of sound and vibration for arbitrary musical source material based on physical measurements is presented. Tactile signals are created by the convolution of "uncoupled" vibration with impulse responses derived from mechanical impedance measurements. Audio signals are created by the convolution of anechoic sound with binaural room impulse responses. Playback is accomplished through headphones and a calibrated motion platform. Benefits of the method include the ability to make multimodal, side-by-side listening tests for audio-tactile stimuli perceived in real music performance situations. Details of the method are discussed along with obstacles and applications. Structural response measurements are presented as validation of the need for measured vibration signals in audio-tactile displays.

1. INTRODUCTION

The purpose of perceptual experimentation is typically to gain a better understanding of how the human system processes its environment. Multimodal experiments, those in which more than one mode of perception are studied simultaneously, are useful because they help eliminate errors that occur when one mode is isolated — an unnatural condition. Practical experiments often study two or three modes simultaneously, and tactile sensation is a natural compliment to audio.

Historically, many audio-tactile experiments have focused on noise-like signals that can be realistically synthesized or measured in a repeatable manner. Recently, the development of advanced entertainment and communication systems has led to a focus on more complex signals such as those generated by musical performance. Controlled synthesis or measurement and reproduction have also become more complicated. In this paper, a method of audio-tactile auralization that can accommodate separate characterization of complex source materials and environmental conditions is presented.

Multimodal experiments have been conducted since some of the early experiments in human response to vibration. Early studies explored the combination of noise and vibration in evaluation of industrial health and vehicle ride quality [12], [10], [9]. Experiments such as that conducted by Howarth and Griffin present the evolution of traditional experimental methods [8]. Simple signals are synthesized to evaluate the relationship between perceived intensity in audio and tactile signals. Broad- or narrow-band noise is fed into a motion platform and headphones. Amplitudes are measured directly during experimentation and compared to subjective responses. Synthesizing signals directly allows for the precisely controlled conditions required to study fundamental psychophysical relationships. However, many complex situations cannot be realistically synthesized. If the researcher is interested in human response to specific situation, he must select a different approach.

An alternative to synthesized signals is to measure them using tactile transducers. Recorded signals have been used to evaluate the perception of synchrony in some of the first audio-tactile experiments in music perception. Daub and Altinsoy present an experiment in which audio and tactile signals were recorded at a listener position in a church and anechoic chamber [2]. The recordings were presented to listeners via headphones and a shaker chair with several time delays inserted between audio and tactile signals. The listeners were asked to identify the signals as "synchronous" or "asynchronous" in a two-alternative forced-choice test. There is no mention of frequency or magnitude calibration for either audio or tactile reproduction systems.

Psychoacoustic test results indicated that the mean user identified the PSS at a tactile delay of −135 ms (negative values indicating a tactile lead) for the pipe organ signal and a −29 ms delay (−43 to −66 ms for subjects with musical experience) for the cello. Daub and Altinsoy drew the conclusion that the PPS was not equal to the *point of objective simultaneity* (POS) and that as a result, the measurement of tactile signals is not required for realistic audio-tactile reproduction. However, if the POS is chosen to be the time at which the signals are most similar, measured using the cross correlation function, the POS and PSS selected by the subjects become much closer. The cross-correlation between the signals was reported to be highest at a −119-ms delay with respect to audio for the organ and a −59-ms delay for the cello. With the POS at the time of maximum correlation, the subjective PSS would be a 16-ms tactile lead for the organ and 5-ms delay for the cello (average of musical listeners). In addition, the authors' conclusion that tactile signals are not necessary for accurate reproduction based on unequal POS and PSS ignores any information about wave propagation, magnitude and frequency contained in structural vibration.

Martens and Woszczyk present a study on the human ability to detect audio-tactile asynchrony [11] using tactile signals synthesized from audio signals. Martens and Woszczyk recorded the sound of a book dropping with microphones and generated a tactile signal by low-pass filtering the audio signal. The signals were reproduced using headphones and a motion platform with time delays inserted in the tactile signal ranging from −40 ms to 40 ms. Two experiments were conducted to identify a *point of subjective simultaneity* (PSS). The experiment is limited to a fairly simple noise/vibration source and only one set of physical conditions. Martens and Woszczyk report that the PSS coincides with the *point of objective simultaneity* (POS). They also report that tactile lags led to more responses of "simultaneous" than tactile leads.

Walker *et al.* have also presented perceptual time-synchrony study for audio-tactile signals produced by musical instruments. In their study, a surround sound microphone technique is used to record the performance of kick drum, piano, pipe organ, and contrabass. Tactile signals were created from a combination of near-field microphone and contact pickup audio transducers. Both were low-pass filtered at 60 Hz. The signals were reproduced using a multichannel loudspeaker system including a subwoofer and a wooden shaker platform measuring 2.4 m by 1.2 m. *et al.* acknowledge and attempt to record large structural resonances in the platform affecting the frequency content of the tactile signals presented. Magnitude calibration is accomplished only by a rough perceptual judgment of matched psychophysical sensation level between audio and tactile signals while seated on the chair. The authors indicate peak acceleration values recorded on the platform range from 0.98 ms^{-2} to 1.93 ms^{-2}, values exceeding those experienced during a rough car ride as reported by Griffin [6]. The POS chosen by Walker *et al.* is based on the synchronized recording and corrected for a time difference between the audio and tactile components of the reproduction system. As a result, the physical POS selected includes the difference in arrival time between the tactile signal measured *near* or *in contact* with the source and the audio signal traveling to the acoustic center of the microphone array.

Overall, the POS values obtained by Walker *et al.* are lower than Daub and Altinsoy's measurements, with the PSS/POS difference ranging from a −30.2-ms to 14.8-ms tactile delay with respect to audio, depending on the instrument. However, these values are in the range of the POS/PSS differences in the Daub and Altinsoy study if the PSS were to be chosen using the point of maximum cross correlation. Walker *et al.* go on to report that frequency content and temporal characteristics of the performance (legato or pizzicato playing styles) influence both the ability to perceived time-order and the resulting PSS.

Recent studies in audio-tactile music perception indicate some confusion about the POS for audio-tactile signals observed in real life conditions depending on the point at which vibration is measured. Propagation times between source and receiver must be considered in the same manner as audio sources. In addition, the authors discuss a need for further study regarding the importance of human response to magnitude and frequencies differences occurring in structural vibration generated by musical sources. The availability of an experimental technique that combines the ability to use musical source material and realistic signals with the ability to sufficiently isolate audio and tactile situations will aid in the progression of audio-tactile musical experimentation.

2. SIGNAL GENERATION

The method of creating audio-tactile stimuli presented in this paper involves measuring source and environmental conditions independently. For the source material, the air and structural borne vibration generated by an acoustic source is measured in isolation of the effects of room acoustics or structural support. The audio-only version of this method has been popularized by room acoustics simulation programs in which music or speech recorded in an anechoic room is convolved with a room impulse response modeled through computer methods — the process referred to as "auralization." In the present experiment, audio is recorded in an anechoic room with a two-channel Head Acoustics HMS V.II binaural "dummy head" microphone. Source material is performed on the contrabass by Michael Bullock.

Structural vibration generated by the source is recorded at the same time. The instrument is decoupled from the supporting floor structure by a small isolation platform, as shown in Figure 1. The spring-damper system upon which the musician rests the contrabass support peg allows the instrument to vibrate in a "free-space" condition above approximately five times the system's first resonant frequency [3]. The system's first resonant frequency is dependent on the mass off the instrument and the spring and damping characteristics of the isolation platform. The mass of the platform should be as small as possible as to minimize the inertia exerted upon the instrument. In this experiment, the isolation platform consists of a 50-mm × 50-mm × 13-mm piece of medium density fiberboard resting upon a 100-mm thick foam pad. The first resonant frequency is measured at 7 Hz while supporting the contrabass, resulting in structural isolation above approximately 35 Hz. As a result, vibration at all frequencies above the instrument's lowest fundamental frequency of 41 Hz are unaffected by the supporting structure.

Vibration generated at the point of contact with the floor, the peg, is recorded using either a force transducer or accelerometer. Here, a PCB Piezotronics T333B50 accelerometer is used to record the vibration waveform generated by the instrument. The apparent mass component of the force generated by the instrument — defined as $F(f) = ma$ — remains

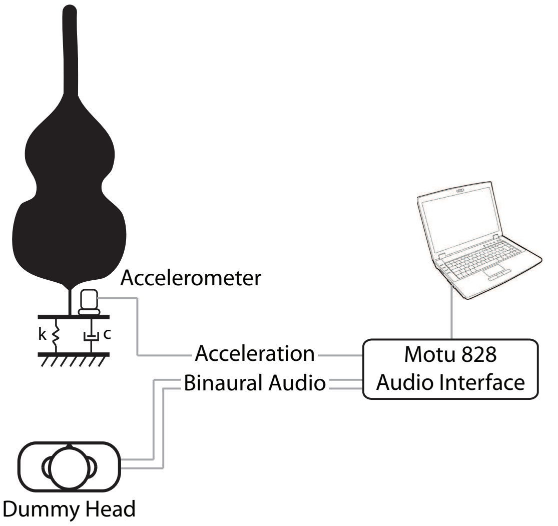

Fig. 1: Diagram of musical source material recording system. Binaural audio is recorded with a Head Acoustics HMS V.II dummy head, the contrabass is isolated from influence of stage vibration by a spring/damper system and recorded with a PCB 333B50 accelerometer.

unknown unless a force transducer is used. Estimation of the instrument's apparent mass lead to errors in calculating the overall scale of the force input to a reference value such as 1 Newton. Calibration of the display system becomes approximate and will be discussed in Section 3. The waveform recorded represents a "decoupled" vibration signal.

Environmental characteristics are obtained separately. The aural environment is quantified by measuring a binaural room impulse response or using another multichannel technique capable of capturing spatial room-impulse responses. Alternatively, the decoupled vibration signal can be recorded while the instrument is being performed in a natural setting — combining the source and environmental characteristics of the audio signal. In the current experiment, the contrabass was performed on the stage of the concert hall in RPI's newly constructed Experimental Media and Performing Arts center (EMPAC).

Structural environments can be quantified through modal analysis measurement techniques as presented in D.J. Ewins book [3]. A function called "accelerance" quantifies the output acceleration normalized by force input for a given structure. Accelerance is defined as a function of frequency and related to mechanical impedance as shown in Equation 1 where ω is frequency, a is acceleration, and Z is mechanical impedance:

$$A(\omega) = \frac{a}{F} = \frac{j\omega}{Z} \tag{1}$$

Accelerance is measured by generating and measuring a force input on a supporting surface at the position the instrument would be located and measuring the acceleration output at the point on the floor or fixed seat at which the listener would be positioned. A 5.4 kg sledgehammer instrumented with a PCB 308B03 accelerometer is used to generate a force impulse. Force is then calculated by multiplying the measured acceleration by the mass of the sledgehammer. Ideally, force would be measured directly using a force transducer.

Acceleration response is measured using a laser doppler vibrometer (LDV) suspended from a stepladder with a bungee cord, as shown in Figure 2, and time-integrating the output through post-processing. The first resonant frequency of the LDV/bungee cord system is observed to be less than 3 Hz, providing isolation of the LDV from the structural vibration above frequencies of approximately 15 Hz.

The range of validity for accelerance measurements is determined by the amount of force generated by the impulse and the resonant frequency of the interface between the hammer and structure, determined by the mechanical characteristics of the materials. Typically, the lower limit frequency is that frequency below which the impact does not generate enough force to excite the structure. For this experiment, the lower limit frequency is determined by the frequencies above which the contrabass is isolated — approx. 35 Hz. The upper point at which frequency response drops by 3 dB is observed at approximately 100 Hz, varying slightly depending on the floor construction. This frequency range of 35 to 100 Hz is sufficient for the measurement and reproduction of whole-body vibration as defined in ISO 2631 by the upper and lower limit frequencies of 0.4 and 100 Hz for the W_k frequency weighting curve given the lowest frequency generated by the contrabass [1]. In

Fig. 2: Structural impulse response measurement equipment. Instrumented sledgehammer used to measure force input, laser doppler vibrometer used to measure force output (isolated from the stage with a bungee cord). Not Shown: 68-kg sand bag placed on a chair used to mass load receiver position. The source position is mass loaded by an experimenter operating the sledgehammer.

further development of the system, measurement of structural response above 100 Hz will be required for research in structural radiation of sound.

Once source and environmental characteristics have been measured, they are combined through convolution of the source audio and tactile signals with the environmental impulse response. Problems associated with measurement of a non-linear structural response are minimized by creating a minimum-phase finite impulse response filter. The convolution process is defined in Equation 2:

$$(f * g)[n] = \sum_{m=-\infty}^{\infty} f[m] \cdot g[n-m]. \qquad (2)$$

The convolved audio signal represents the original source material filtered with delayed reflections and frequency characteristics. The direct sound of this signal is calibrated to match the direct sound recorded in the anechoic room. If the audio signal is measured directly in the target environment, the level at the ear is calibrated to match those recorded with the binaural microphone. The convolved vibration signal represents an absolute-scale, calibrated acceleration that would be experienced at the receiver location.

3. AUDIO-TACTILE DISPLAY

Playback of the convolved audio-tactile signals is accomplished through an audio-tactile display system, consisting of binaural audio presented through headphones and whole-body vibration presented by a motion platform. A key factor in the decision to use a binaural technique was the ability to control cross-talk between the two modes of perception during experimentation. Some noise is inherent in any motion platform driven by hydraulics, electric motors or electrodynamic shakers and must be accounted for in any current tactile experiments. In this experiment, the electrodynamic shaker device used to generate tactile signals effectively turns the entire platform into a soundboard, rendering audible the tactile waveform. The use of a multi-channel audio format would require some mitigation of platform noise, possibly through constructing an isolated boundary layer above the platform surface with penetrations allowed to support the seat.

Closed-ear Sennheiser HD280 headphones are used for audio presentation; selected primarily for their high levels of sound isolation. Gain settings for headphones amplification are calibrated using the HMS V.II system. Exact magnitude and frequency response calibration of binaural presentations is a complex task and a point of continuing contention [5]. The reader is encouraged to employ any method preferred. In this experiment, overall linear sound pressure levels generated at the ear of the dummy head are calibrated to within ± 1 dB of measured values without frequency response calibration.

Tactile signals are reproduced with a motion platform constructed of two layers of 20-mm plywood laminated together and supported by 38-mm × 140-mm wood framing as shown in Figure 3. A 76-mm foam pad is placed under the platform to allow for vertical freedom of movement. The platform is constructed in the stiffest manner possible to raise the first resonant frequency of the system above the frequencies of interest. However, post construction analysis indicates this objective was not accomplished. The low frequency range of interest and inherent frequency dependence of the speed of the dispersive bending waves responsible for whole-body vibration in structures leads to resonances despite stiffness (dispersive waves are discussed in Section 4). As a result, the platform requires significant calibration in the frequency domain to account for structural resonances and anti-resonances.

Structural vibration is generated by an electrodynamic shaker (Buttkicker LFE) and its associated 1000-watt amplifier. The shaker is rigidly attached with four bolts to the bottom of the platform directly below the seat, which is also rigidly attached to the platform. The use of four bolts results in the ability of the shaker to induce torsional or rotational vibration into the platform. In this experiment, a small degree of rotational and horizontal vibration is expected due to chair and platform dynamics. Such off-axis vibration would also be observed in real-world conditions. If truly unidirectional motion is desired, the shaker must be attached through a single point connection with stiffness in only one dimension and a guide system installed on the platform.

Acceleration magnitude is calibrated at a single point located on the bottom-center of the seat. The single point of calibration is a compromise necessitated by the variation in vibration magnitude observed across the platform. The most significant interface between the human body and the platform occurs at the seat. However, structural dynamics of the platform result in a difference between seat-bottom and floor vibration that is greater than in architectural environments. Further development of a platform in which floor vibration can be adjusted independently of seat vibration would allow for more accurate reproduction.

Fig. 3: Motion platform used in multimodal presentation of audio-tactile stimuli. Sennheiser HD280 headphones are used for audio presentation.

If force input generated by the musical source is measured using a force transducer, an acceleration sensitivity in ms^{-2}/V can be measured on the platform. The scalar sensitivity adjustment is then applied to the electrical signal fed to the platform. If musical source is recorded with acceleration, as in the current experiment, the platform calibration is estimated in the following manner: 1) A tactile signal is created by convolving a decoupled vibration signal with a structural impulse response. 2) The same vibration source is recorded, this time coupled with the structure. Structural vibration is recorded at the same point as the output of the structural impulse response. 3) The convolved signal is reproduced with the platform and gain is adjusted to match the signal measured with the source coupled to the structure.

Table 1: Total harmonic distortion plus noise measured for 11 frequencies at the center-bottom of the platform seat at calibrated gain setting.

Freq. (Hz)	THD+N (dB)
30	26.2
33.6	29.9
37.8	29.8
42.4	27.3
47.6	27.1
53.4	30.6
60	31.6
67.2	28.8
75.6	31.6
84.8	28.5
95.2	30.6

Structural systems naturally produce non-linear responses. In natural environments, this non-linearity introduces difficulty in the measurement of structural impulses. In the reproduction system, the non-linearity amounts to distortion of the tactile signal. Initial investigations identified non-linear response in the shaker even without connection to the platform. Combined with the platform response, some level of tactile signal distortion is expected. In order to quantify the amount of distortion and ambient vibration, total harmonic distortion + noise is measured at the seat-bottom for 11 frequencies. The resulting values are presented in Table 1.

The values in Table 1 are measured at the gain setting selected during calibration. Harmonic distortion + noise levels generated by only 2 of the 26 combined source/environment tactile signals exceed the absolute threshold of perception of 0.01 ms^{-2} peak.

Frequency response is calibrated using a cross-correlation transfer function measurement technique and swept-sine signals. Signal input is band limited between 10 and 100 Hz with 10th-order Butterworth filters. The un-calibrated transfer function is inverted and used to create a minimum-phase calibration filter. The transfer functions, measured before and after calibration, are presented in Figure 4. Frequency calibration is performed with an 82-kg subject seated on the platform.

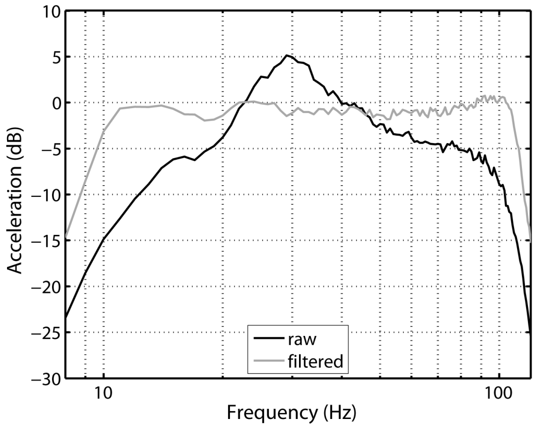

Fig. 4: Frequency response measured at the bottom of hard wooden seat mounted to the motion platform before and after calibration. Measurements are made with a 82-kg human subject seated on the platform.

Signals reproduced by the platform are filtered off-line. The minimum phase nature of the structural impulse response filters means that propagation time information is lost. As a result, propagation times are calculated by finding the peak of the cross-correlation function between the input and output accelerations measured by the structural impulse response. This single value is inserted as a time delay in the reproduction system. The use of calibrated time differences measured between audio and tactile signals requires that time delays inherent in the audio-tactile transducers and reproduction system be removed. To calibrate propagation times in the reproduction system, a maximum-length sequence test signal is reproduced simultaneously by the headphones and shaker while being recorded with the dummy-head microphone and accelerometer. The maximum value of the cross-correlation between these recorded signals is observed at 3 ms with the tactile signal lagging. Consequently, a 3-ms delay is added to the audio signal to align it in time with the tactile signal. Drawbacks of this method are discussed in Section 4.

4. RESULTS OF STRUCTURAL VIBRATION MEASUREMENTS

The development of this audio-tactile auralization system was initiated by a desire to explore the influence of vibration created by musical performances in its natural form across several structural environments. In the course of development, structural impulse responses were measured on 5 different floor constructions at 3 or 6 locations each. The results of these measurements provide interesting validation of a calibrated reproduction system in which source material and environmental conditions can be implemented separately.

Measurements are conducted at 1, 2, and 4 meters distance in two directions of propagation (when possible) on each floor. Figure 5 presents the magnitude of vibration response to an approximate 1 Newton force impulse measured for 26 different source/receiver positions. Magnitude is presented as acceleration in ms^{-2} between 10 and 100 Hz weighted by the frequency function W_k defined in ISO 2631. This frequency weighting metric was developed to represent subjective human response in a similar manner to the A-weighted decibel for audio signals. A linear vertical axis is used in accordance with the linear growth of sensation level with physical magnitude as reported by Howarth and Griffin among others [7]. The difference between maximum and minimum values measured is 0.97 ms^{-2} W_k (39 dB) with the largest difference observed on a single floor construction of 0.93 ms^{-2} W_k (26 dB).

The physical magnitudes measured on the 5 relatively similar stage constructions represent a broad range of associated “sensation levels.” The values presented do not correspond to any normally experienced vibrational source, but depict the variation in structural response to the same input. The range observed drastically exceeds the just-noticeable-difference in vibration magnitudes reported by Morioka and Griffin of approximately 10% in the region of 0.1 to 0.5 ms^{-2} r.m.s. [13]. According the Griffin’s *Handbook of Human Vibration*, these magnitudes, occurring as the result to a sledgehammer impact, would elicit a response ranging from “probably imperceptible” to “very strong perception” and reach the maximum typical values experienced in architecture [6]. The data also shows that vibration decays with distance at differing rates dependent on structural materials and construction methods in addition to the direction of propagation on a single structure.

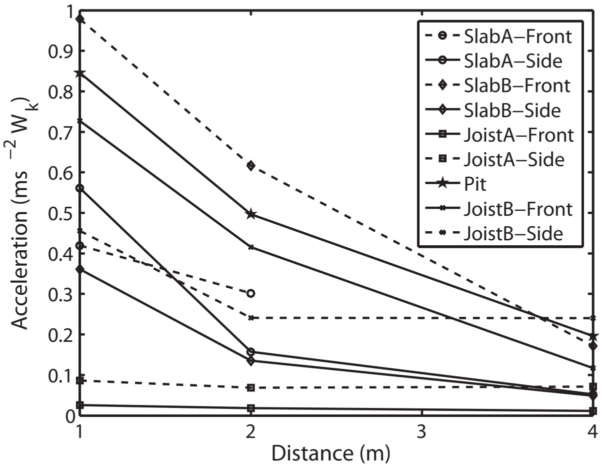

Fig. 5: Structural vibration measured in response to a 1 Newton force impulse between 10 and 100 Hz.

Variations in frequency content are also observed to vary with floor construction. Figure 6 presents magnitude spectra measured on two wood floor constructions. The most pronounced differences observed occur between wood joisted structures and highly damped concrete sleeper/slab structures. The structures exhibiting higher levels of damping result in less modal behavior and smoother frequency response characteristics. It is unknown at this point what impact these variations in frequency response may have on the perception.

Structural impulse responses also include information on the temporal characteristics of the vibration response. The structural waves controlling human vibration and under investigation in this study are bending waves. Bending waves are dispersive, having a wave speed that is proportional to frequency as shown in Equation 3. The wave speed is dependent on physical properties of the material — Young’s Modulus E, second moment area of the cross section I of the neutral axis, and mass per unit length m — and the traveling wave’s wavenumber k and frequency ω [4].

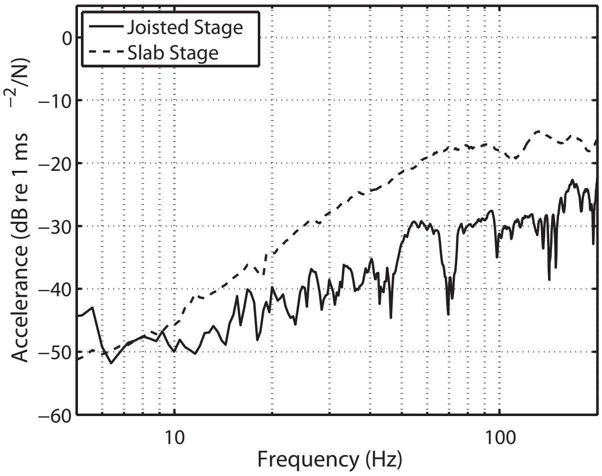

Fig. 6: Structural vibration frequency response measured at 2 meters on wood floors supported by traditional wood joists and a concrete slab.

$$c_{\text{bending}} = \omega/k_{\text{bending}} = \sqrt{\omega}\left(\frac{EI}{m}\right)^{1/4}. \quad (3)$$

The most important implication of the dispersive nature of bending waves in audio-tactile experimentation is that structural vibrations of different frequencies will travel between source and receiver at different speeds. High-frequency portions of the signal will arrive at listeners before low frequencies. Traditionally, sound is considered to travel faster in solids than air. The sound spectrum includes frequencies ranging up to 20 kHz, and the frequency dependence shown in Equation 3 leads to high wave speeds. However, when only the low frequencies associated with whole-body human vibration are considered, structural vibration wave speeds are not necessarily faster than in air.

Figure 7 presents tactile propagation times measured as described in Section 3 along with an audio propagation time curve constant for each set of 3 distance measurements. The data shows that propagation times calculated using the cross correlation method are *greater* than that of the audio signal for all but one structure/direction combination. The result is that the tactile signal lags the audio signal in nearly all conditions by up to 74 ms depending on construction and direction of propagation.

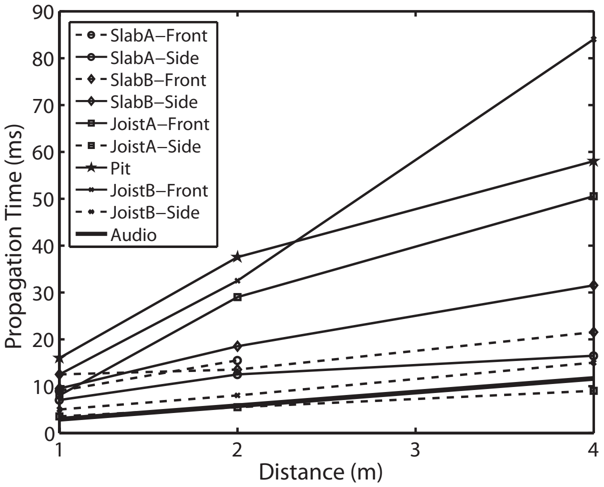

Fig. 7: Structural vibration propagation times measured on 5 different stage constructions at 1, 2 and 4 meters in perpendicular directions. Audio propagation times presented for reference.

The propagation times presented in Figure 7 are calculated in the same manner as the study conducted by Daub and Altinsoy [2]. This method of calculation — finding the maximum value of the cross-correlation function — ignores the dispersive nature of bending waves by the point of maximum correlation in the broad band signal. It is possible that the human system of perception utilizes a different method of assessing audio-tactile synchrony due to its constant exposure to audio signals with predictable frequency-independent wave speeds, and tactile signals with frequency-dependent propagation that vary constantly in daily life. The human system may be able to detect asynchrony as reported by Daub and Altinsoy [2] and Walker *et al* [14], but largely ignore it due to its constantly fluctuating value.

These studies present support for the ability to detect asynchrony, but reported discrepancies in objective and subjective points of synchrony require further validation with the consideration of dispersive waves. One method of analysis would be to filter structural impulse responses or coincident audio-tactile measurements into narrow bands before using the cross-correlation function to find the point of perceptual time synchrony. The frequency-dependent results could then be used in combination with subjective studies utilizing signals that accurately represent temporal characteristics experienced in natural environments. Alternative filtering techniques should also be employed.

5. SUMMARY

The auralization system presented in this paper provides a basis for the further development of a platform for audio-tactile experimentation in which source and environmental conditions can be evaluated independently. The development of this system will require the adoption and understanding of modal analysis techniques. Measurement and signal processing methods must account for a frequency range of human response extending down to 0.4 Hz, or the lowest frequency generated by the source of interest. Bending waves with frequency dependent speeds of sound must be considered in the analysis of temporal characteristics including audio-tactile synchrony and waveform composition.

Absolute magnitude and frequency response of the tactile portion of audio-tactile displays must be considered with the same attention to detail as is typically employed in the design of a critical listening room. In ideal conditions, a complete modal analysis of the platform would be used to evaluate platform response and could be compensated for at the point of human contact. In practice, platform response may be compensated for with input frequency filtering. Perceptual impact of platform response characteristics is an area requiring further research. Magnitude response should be calibrated to an absolute level for at least one measurement position. Time delays between audio and tactile presentations can be measured and compensated for by measuring the cross-correlation function between the two.

Structural measurements indicate that tactile signals can vary drastically in environments in which aural acoustical conditions remain fairly fixed. In a hypothetical explanation, a listener who changes seating positions in a constant radius around an omnidirectional sound/vibration source coupled to the floor would experience different tactile sensation levels with a constant audio signal (considering direct sound only). A whole new set of levels would then be presented if the source and listener moved into a different room. A listener walking across a single floor construction may experience up to 26 dB differences in frequency weighted acceleration response to the same source. “Peakiness” of modes observed in the frequency spectrum varies with stage construction. Tactile signals are observed to lag audio signals in most situations, with delays of up to 74 ms when measured with the broad-band cross-correlation function. Further research is proposed to find the best method of quantifying the perception of audio-tactile synchrony with the consideration of dispersive bending waves.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] ISO 2631-1 mechanical vibration and shock - evaluation of human exposure to whole-body vibration - part 1: General requirements, 1997.

[2] M. Daub and M. E. Altinsoy. Audiotactile simultaneity perception of musical-produced whole-body vibrations. In *CFA/DAGA'04 (Congrs Joint / Joint Congress 7me Congrs Franais d'Acoustique CFA / 30th German Annual Meeting for Acoustics DAGA)*, Strasbourg, France, 2004.

[3] D.J. Ewins. *Modal Testing: Theory and Practice.* Research Studies Press, 1986.

[4] F. Fahy and P. Gardonio. *Sound and Structural Vibration: Radiation, Transmission and Response.* Academic Press, Oxford, UK, 2007.

[5] D. Griesinger. Accurate timbre and localization of binaural recordings through headphones using sound pressure measurement at the eardrum. *J. Acoust. Soc. Am.*, 125(4):2484–2484, April 2009.

[6] M.J. Griffin. *Handbook of Human Vibration.* Elsevier Academic Press, 1990.

[7] H. V.C. Howarth and M. J. Griffin. The frequency dependence of subjective reaction to vertical and horizontal whole-body vibration at low magnitudes. *J. Acoust. Soc. Am.*, 83(4):1406–1413, April 1988.

[8] H.V.C. Howarth and M.J. Griffin. Subjective response to combined noise and vibration: summation and interaction effects. *Journal of Sound and Vibration*, 143(3):443–454, 1990.

[9] R.H. Kirby, G.D. Coates, P.J. Mikulka, T.K. Dempsey, and J.D. Leatherwood. Effect of vibration in combined axes on subjective evaluation of ride quality. *Journal of Applied Psychology*, 62(6):727–734, 1977.

[10] A. Kjellberg, B.O. Wikström, and U. Dimberg. Whole-body vibration: exposure time and acute effectsexperimental assessment of discomfort. *Ergonomics*, 28(3):545–554, 1985.

[11] W. L. Martens and W. Woszczyk. Perceived synchrony in a bimodal display: Optimal intermodal delay for coordinated auditory and haptic reproduction. In *Proc. of ICAD 04-Tenth Meeting of the International Conference on Auditory Display*, Sydney, Australia, July 6-9, 2004.

[12] T. Miwa and Y. Yonekawa. Measurement and evaluation of environmental vibrations. part 2. interaction of sound and vibration. *Industrial Health*, 11:177–184, 1973.

[13] M. Morioka and M. J. Griffin. Difference thresholds for intensity perception of whole-body vertical vibration: Effect of frequency and magnitude. *J. Acoust. Soc. Am.*, 107(1):620–624, Janurary 2000.

[14] K. Walker, W. L. Martens, and S. Kim. Perception of simultaneity and detection of asynchrony between audio and structural vibration in multimodal music reproduction. In *Proc. Audio Engineering Society 120th Convention*, Paris, France, May 20-30, 2006.