Wireless Sensor for Monitoring Acoustic Induced Vibration

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***Abstract*—Acoustic induced vibration can cause museum art objects to deteriorate at a very rapid pace, thereby endangering the cultural heritage they conserve. Here, wireless triaxial MEMS accelerometer nodes were used to monitor the effect of loud and live music played during social events at the Walters Art Museum on mock art objects. During the social event, continuous wireless vibration activity monitoring was performed from sensors placed on respective blocks with the art object under test to provide real-time vibration activity information. The vibration induced by the music, as well as the vibration propagation through the specific object via the mounting or display mechanism were evaluated. The loud music played generated high acoustic energy that excited the object vibration modes and placed the object at risk of induce fatigue cracking and "walking", all of which can potentially cause catastrophic damage in extreme cases. The acoustic field with an intensity of 90 dB induced the highest level of vibration. The display block orientations were observed to contribute to the vibration activity, wherein, the vertical orientation induced higher levels of vibration when compared to the horizontal orientation.**

***Keywords*—Acoustic; vibration; monitoring; wireless; sensors**

I. Introduction

Damage to artifacts has been observed in various museums worldwide and has been attributed to some source of vibration induced in the art objects [1]-[4]. Most museum are stocked with a variety of displays that showcase objects made of clay, metal, porcelain, ivory and glass, wherein scientists and curators determine the way in which these art objects are conserved and displayed based on their composition. At the Walters Art Museum objects are displayed in a variety of ways including cases enclosed in Plexiglas, placement on Komatex display blocks, and/or mounted to the wall or left freestanding. Acoustic-induced vibrations from loud, live music in the museum environment may pose a major risk to museum objects. As a result, it is important to determine how to best protect the museum collection and monitor the vibrations induced in objects close to the acoustic source. Social events are traditionally held in the main atrium of the Walters Art Museum. Along the balcony, there are wall-mounted displays showcasing the German Medieval Salt Glazed Stoneware as shown in Fig. 1. After social events, conservators identified objects that had experienced "walking", paint chipping, and cracking as a result of the relatively large stresses developed in the object. "Walking" is a phenomenon in which induced vibrations cause the museum artifacts to move across their display blocks. When "walking" occurs, artifacts are at risk of toppling over and damaging themselves and the surrounding artifacts.

Fig. 1. Art objects in the Walters Art Museum show evidence of "walking" across their displays. Prolonged and repeated exposure to vibrations from music events is considered to be the cause.

Although there are no present studies on the effect of acoustic induced vibration activities on museum artifacts, there are significant amount on the effect of construction vibration on artifacts in the museum [1], [5]. It was observed that very fragile artworks were damaged by non-construction levels of vibration at a frequency of 20 Hz [5]. Generally, residential homes exhibit dominant natural frequencies in the range of 4–12 Hz [6], thereby exceeding these frequency limits amplifies the natural object's response frequencies, where larger vibrations from higher frequencies become more dominant. A construction vibration monitoring system developed by Serotta et al. focused on the effect of resonant frequencies of a cantilever shelf (seen as a simple cantilever beam) holding an art object [4]. They demonstrated that the vibrations induced in the beams is dependent on the frequency content characteristics of the excitation with respect to the natural frequency of the shelf (excitation duration), as well as on the amount of dampening. The vibration amplification can be mitigated by avoiding excitation at the resonant frequency and increasing the dampening of the vibrations.

The work of Thickett further supports the observation that the main effects of the vibration activities were objects falling off display shelves, worsening of existing damage/cracks, and objects "walking" off the shelves when investigating the vibration induced in artworks from museum visitors walking on weaker and/or older floors. The mass of the object, contact surface area, and the material characteristics of the object were found to have an effect on the objects' propensity to "walk" along the shelves [5]. Additionally, the type of damage observed at different vibration levels were cataloged and summarized for the building project at the British Museum. The most common damage observed were loss of loosely bound pigment on a polychrome statue and the abrasion against mounting pins of a terracotta plaque [5].

The closest work relating to acoustic induced vibration monitoring, is the utilization of sound waves generated by passing aircraft inducing vibration activities in floors, walls, windows and indoor structures of homes [7]. Therefore, in order to investigate the effect of acoustic induced vibration activities on German Medieval Salt Glazed Stoneware, we utilized wireless triaxial MEMS accelerometer nodes [8] to gather vibrational data in z-direction (upward and downward directions) of art objects in real-time under various sound frequencies and intensities.

II. Experimental Section

To study the vibration induced in art objects in the presence of loud, live music; high-speed ±2g G-Link®-LXRS® wireless accelerometer nodes were used for data collection. Fig. 2 shows the diagram of the system from the wireless sensor node to the gateway. The wireless sensor node consists of internal temperature sensor, memory, ADC, microcontroller and radio transmitter. The analog-to-digital converter (ADC) digitizes the signal from the accelerometer and the wireless transceiver communicates the digitized signal to the project server. We chose to monitor the vibration in the z-direction because previous research suggests that dominant vibrations in art objects occur in upward and downward directions [9]. The nodes were configured to sample the acceleration data at a rate of 512 Hz. The gateway side consists of radio receiver and microcontroller to send the sensor signal to internet terminals. The gateway design required that it be placed in close proximity to a power source (an AC outlet).

With this wireless accelerometer sensing system, it is possible to access the vibration activity information of the monitoring nodes via an internet-connected device running Node Commander® software. Initial sound intensity experiments were performed in a vibration isolation chamber as shown in Fig. 3 to measure the vibration induced by the music without the interference of external sound. The layers of padding and suspended platform employed in the chamber further dampen any external vibration coming from outside the chamber. Studies were conducted at various sound intensities. The accelerometer sensors were used to monitor art objects placed on pedestals and display blocks in such a way that they provided an indication of the local responses.

The preliminary testing showed that the acoustic induced vibration activities were produced with a predominant vertical component because the horizontal vibrations were comparatively low for all the cases evaluated. Therefore, in this work all measurements were acquired as single z-axis (in the vertical direction) instead of the triaxial.

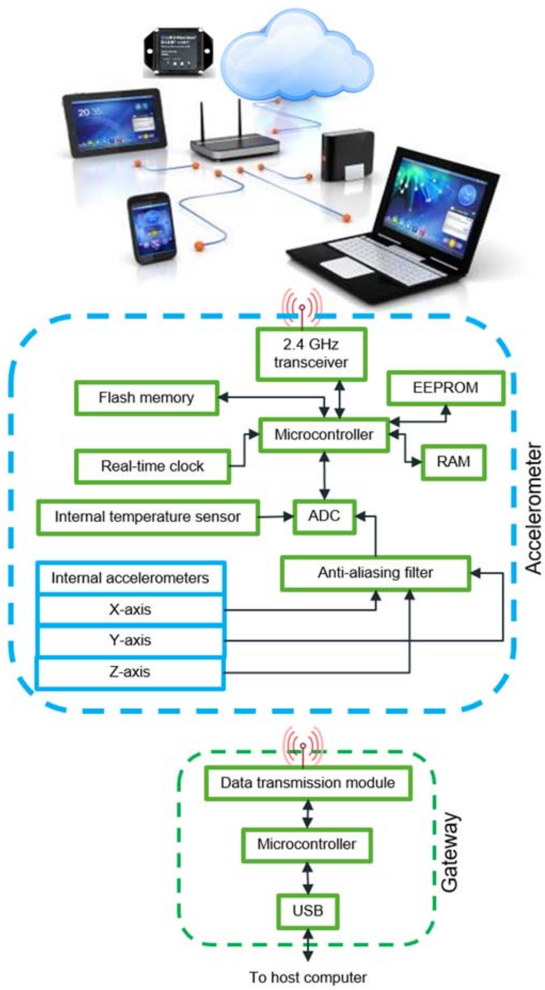

Fig. 2. Diagram of accelerometer and gateway system architecture.

Fig. 3. Experimental set-up using a vibration isolation chamber.

III. Vibration Monitoring Principle

The monitoring network consisted of at most two sensors (accelerometers), a gateway and a wireless network. The accelerometer enables the monitoring of the vibration amplitude. The accelerometers chosen exhibited increased sensitivity (and consequently lower input range). The accelerometers (±2g G-Link®-LXRS® wireless triaxial accelerometer nodes) were used to measure the acceleration in the x-, y-, z-directions. However, in our preliminary testing, we found the z-direction to be the dominant component, as mentioned previously. Each accelerometer communicated wirelessly with the gateway (WSDA®-Base-104-LXRS®). For experimental purposes, the accelerometers were laid on the desired surface unmounted/unclamped. In laboratory testing, this configuration was demonstrated to provide accurate measurements while using the existing Wi-Fi network. The server was used as the central processing point for all the signal packets.

IV. Results and Discussion

Artwork at the Walters Art Museum is displayed under a number of conditions. Herein, the display conditions evaluated include: display case with or without Plexiglas case cover; Komatex display block placed horizontally (relatively low height above the display floor) or vertically (relatively high above the display floor); and the display case mounted against a wall or left freestanding. Lastly, the vibration responses of the mock art object (goblet) was measured for a variety of frequency and intensity levels.

Musical performers are instructed by the museum to not play music at an intensity level greater than 80 dB. As a result of this request, the intensity experiment was performed in the laboratory to determine whether or not varying the intensities at which music is played will increase the vibration induced in the goblet. Two accelerometers were used, wherein one accelerometer was placed on the top left corner of the vibration isolation chamber to monitor any vibrations that may be emitted from the speakers outside the isolation chamber. The other accelerometer node was placed inside the isolation chamber to detect acceleration along the z-axis in response to the vibrations induced by the sound. Dell Altec Lansing ADA215 speakers were used to play music at a range of intensities starting from 70 dB and increasing in increments of 5 dB until 90 dB. Two Komatex display blocks were placed into the isolation chamber. The first block held the speakers which were not in direct contact with any other surfaces in the isolation chamber and the second block held the goblet and accelerometer. In the isolation chamber, music was played at a starting intensity of 70 dB over a 10 second sampling period at a frequency of 512 Hz. Fig. 4 revealed that the normalized acceleration increases with the increase in music intensity and producing a perceptible increase in vibration activities. Thereby, the higher intensity excitations resulted in greater accelerations, which is characteristic of greater acoustic induced vibration. The largest vibration change induced was observed when the music intensity became very loud at the intensity of 85 dB to 90 dB.

Another approach was taken to further investigate the goblet in a display case created by the Walters Art Museum consisting of a medex base stand with a detachable medex display platform on top of the base that featured a removable Plexiglas covering. A single accelerometer node was placed in the display case to monitor the vibration activity. James B. Lansing (JBL) SRX series speakers were placed at a distance of 42 feet and were used to deliver 48.1 Hz and 440 Hz tones at which vibration amplification is expected at a mid-range intensity of 90 dB and a max intensity of 96 dB. As the tones were played, the accelerometer node sampled data at 512 Hz for seven seconds. Fig. 5 illustrates that at midrange intensity and frequency, the vibration induced in the presence of the 'no Plexiglas' resulted in higher vibrational activities when compared to those observed in the presence of the Plexiglas covered. Even though at lower frequency and enclosed in the Plexiglas cover, the vibrations resulting from the tone had a slightly greater vibration, thereby indicating that at lower frequency the vibration propagates through the Plexiglas cover to the object being displayed. This inherent conservation strategy via Plexiglas cover made it unattractive options for lower frequency acoustic signals. However, this presents a good option for higher acoustic signals. Additionally, a given museum art object may have a natural frequency between 20–30 Hz and excitation at the frequency of 48.1 Hz thus induce vibrations that is further amplified in the museum art object because the tone frequency coincides with regions of greater response energy.

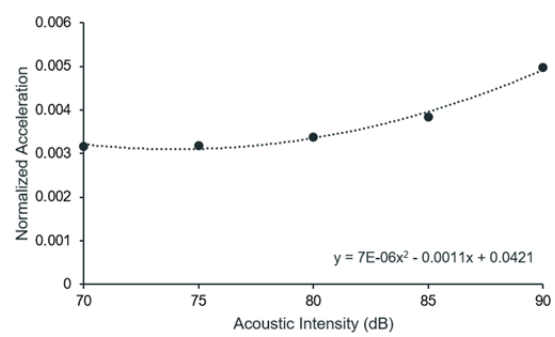

Fig. 4. Normalized acceleration plot depicting the relationship between the music intensity and the vibration induced.

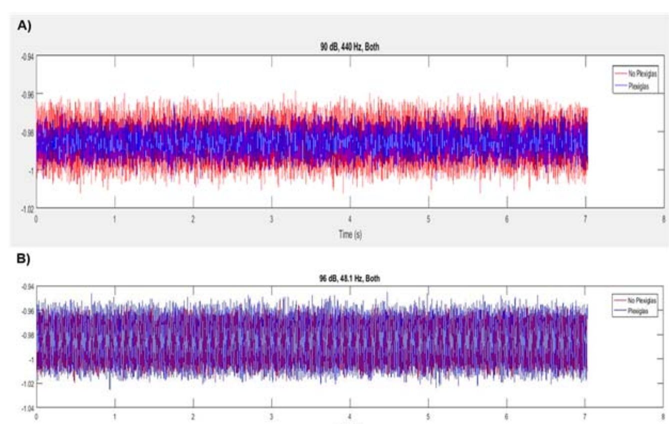

Fig. 5. Vibration induced at (A) 440 Hz (90 dB) and (B) 48.1 Hz (96 dB) in the absence and presence of Plexiglas cover. A composite plot is depicted to compare the normalized acceleration. [No Plexiglas: Red and Plexiglas: Blue].

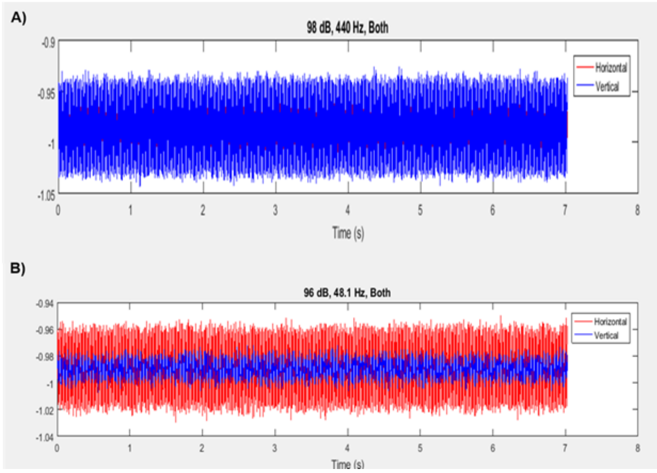

Fig. 6. Vibration induced at (A) 440 Hz (98 dB) and (B) 48.1 Hz (96 dB) in the horizontal and vertical Komatex display block orientation. A composite plot is depicted to compare the normalized acceleration. [Horizontal: Red and Vertical: Blue].

Fig. 7. Vibration induced at (A) 440 Hz (80 dB) and (B) 48.1 Hz (90 dB) when display case is freestanding or mounted to wall. A composite plot is depicted to compare the normalized acceleration. Freestanding: Red and Mount to Wall: Blue].

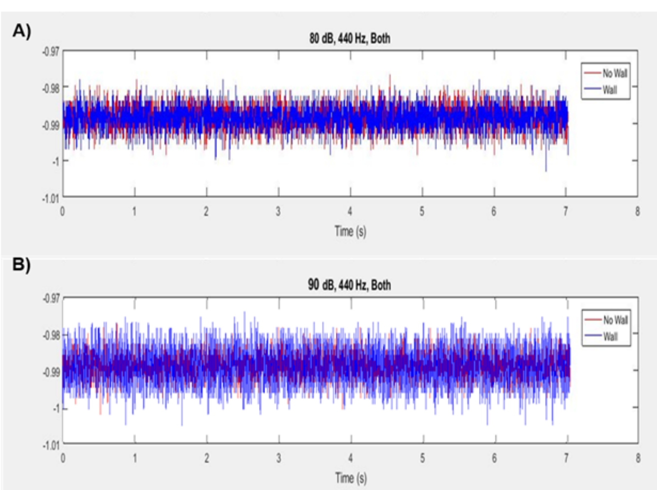

Fig. 8. Vibration induced at (A) 440 Hz (80 dB) and (B) 48.1 Hz (90 dB) when display case is freestanding or mounted to wall. A composite plot is depicted to compare the normalized acceleration. Freestanding: Red and Mount to Wall: Blue].

The Komatex display block orientation (horizontal versus vertical) was found to play a critical role in the propagation of the induced vibration activities. The approach involved the placement of the Komatex display block initially in the horizontal orientation on the platform followed by the goblet and the accelerometer node. The setup was then covered with Plexiglas and interrogated at 440 Hz (98 dB) and 48.1 Hz (96 dB). This process was then repeated with the block placed in the vertical orientation. It is apparent from Fig. 6 that the vertical orientation induces an increase in vibration at high intensities and midrange frequencies (440 Hz, 98 dB). Conversely, the 96 dB intensity paired with the 48.1 Hz frequency caused substantially more vibration activities in the horizontal block display orientation than in the vertical block display orientation. These results indicated that the dominant motions experienced by the display block from the tones were restricted to a localized area.

In museum settings, display cases are commonly left freestanding or mounted to a wall as shown in Fig. 7. To gain a better understanding as to whether the wall intensifies or dampens the vibration induced in the art object being displayed, the initial test focused on a freestanding display case placed 16 feet in front of the speakers. The goblet was then placed in the center of the display platform and the accelerometer node was placed on the back corner of the platform, all of which were enclosed with the Plexiglas cover and interrogated at 440 Hz (80 dB) and 48.1 Hz (90 dB). The interrogation was repeated with the display case firmly mounted to the wall. At a frequency of 440 Hz, the wall appeared to have a slight impact on the vibration induced in the art object. This represents the mechanical vibration in the display case being amplified relative to the original source excitation (the wall). Thereby, we observe more induced vibration on the object as shown in Fig. 8. This increase in vibration may be due to the inertial forces of the object.

Overall, all the conditions tested suggested that different frequency tones/sounds at various intensities induces vibrational activities in museum art objects. Once the acoustic source was removed, the vibration subsided. There were some cases in which the induced vibrations were significantly larger, thereby demonstrating the importance of acoustic induced vibration activity monitoring. Additionally, it was discovered that there was a strong correlation between the Plexiglas and the vibration activities at low frequencies. Further investigation suggested that the vibration induced in the Plexiglas propagated to the surrounding objects, which likely exacerbated the vibration activities presented by the Plexiglas. Clearly, mitigation strategies must be employed to reduce the risk of damage to the museum art objects. For instance, Sorbathane has been shown to be highly effective in mechanical vibration mitigation and it may find potential application in the mitigation of acoustic induced vibration. In this case, it may be necessary to carefully monitor the dampening performance of the Sorbathane over time.

V. Conclusion

As a means of attracting more patrons, museums host live musical performances, although they are uncertain about the effect it may have on the artifacts. While it may not be apparent, the vibrations that come from the music being played may cause damage to the artwork upon repeated exposure. Here we successfully demonstrated the effect of acoustic induced vibrations on a museum art object using wireless triaxial accelerometer sensor nodes. The vibrations induced by acoustic tones of differing frequencies and intensities had an impact on the art object. Overall the presence of the Plexiglas can mitigate the vibration activities experienced on the surface of the display platform when exposed to high frequencies, however, at lower frequencies this is not the case. For example, it was observed that at lower frequencies, the vibration activities were large when objects are enclosed in the Plexiglas cover, and thus this induced vibration was further amplified by the excitation frequency, which then propagated to the display block and hence the art object. Therefore, the continued use of the Plexiglas case covers is encouraged, although questions arise regarding whether or not the current method of installation or the superiority of the Plexiglas and its material properties are sufficient as opposed to other materials.

A primary concern of art conservation efforts is the "walking" of art objects. With added height, this concern grows as the object is more likely to be irreparably damaged. It would appear that at reasonable midrange intensities, the shorter horizontal orientation is preferred, as it results in less overall vibration, thereby contributing less to the "walking" phenomenon. Lastly freestanding display cases seem to show an overall lower propensity to vibrate. Implementation of these findings in addition to Sorbothane, Ethafoam, and other foam materials could reduce the vibrations experienced by museum art objects by effectively dampening the vibration and mitigating the destructive impacts of vibration induced by acoustic excitation in museums. These mitigation strategies are critical for the proper care and conservation of cultural heritage.

ACKNOWLEDGMENT

The authors would like to extend their deepest gratitude to The Walters Art Museum and The Andrew W. Mellon Foundation.

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