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Stethoscope-based detection of detorqued bolts using impact-induced acoustic emissions

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Results of a preliminary study investigating a simple method for detecting looseness in bolted fasteners of a steel structure are presented. Extensive research by many investigators demonstrates that the frequency response of a bolted structural member changes when one or more bolts are loosened. A simple and effective method for detecting looseness can be applied to bolted joints, using inexpensive and commonly-available equipment and software. The difference between spectrograms associated with tight and loose bolts is clearly apparent due to the presence of a tell-tale mode when one or more bolts are loosened. Further, a striking difference can be elucidated between audio signals associated with tight and loose bolts, with only minimal post processing. A time-frequency spectrogram was used to identify higher-order modes that are affected by looseness in a horizontal I-beam with bolted connections. One higher-order mode was found to be particularly sensitive to bolt loosening. Results show that the natural frequency associated with a higher-order mode provides a tell-tale acoustic response that can be elicited with an open-output impact test using a common hammer.

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Introduction

The goal of a structural-health monitoring (SHM) system to detect damage in structures has been pursued for many years. There are many studies demonstrating that the dynamic response of a structure changes due to degradation of joints between members of the structure. Non-destructive evaluation (NDE) methods include built-in sensor/actuator systems operating beyond the audio range (*eg*., Park *et al*., 2000), and acoustic emission (AE) monitoring for both local and global failures (*eg.*, Nair and Cai, 2010). On a more elemental level, the dynamic response of a small bolted joint was measured in a laboratory and compared to an analytical model developed to include nonlinear effects such as sticking and sliding (Feenstra, *et al.*, 2005). Esmaeel *et al.* (2012) published a study of a bolted flange in a pipeline that was degraded by progressively loosening bolts. The structure was impacted with a hammer and the dynamic response was measured by an array of piezoelectric sensors. Results indicated that loose bolts were detected in all cases. As a further refinement, a more precise hammer impact allowed quantification of the looseness in the joint (Razi *et al*., 2013). The possibility of detecting loosened bolts in a full-size steel frame structure was explored in a preliminary study (Guarino and Hamilton, 2009), which showed a marked difference in open-ended impact-induced spectra recorded before and after bolts in a connection were loosened.

This paper presents results of a study with the goal of identifying a tell-tale signal associated with loosening of a bolted connection in a steel space frame, while retaining the basic simplicity of earlier efforts.

Data were obtained using an inexpensive electronic stethoscope placed by hand for each record. The impact source was a hammer strike from a common one-pound claw hammer. The response was "open-ended," with no reference to the input signal. Audio data were recorded for twenty-six combinations of tight and loose bolts. Spectrograms and audio tracks from each record were compared to see if a tell-tale sign could be used to detect loose bolts in a connection.

Methods

A horizontal, standard W 27 X 84 I-beam fastened at both ends to vertical steel columns in a full-sized space frame was used in the study. The horizontal beam is part of a two-story steel frame comprised of structural I-beams and located in an enclosed building. The beam spans two vertical columns in the structure. Two thin spacer plates were welded between the ends of the beams and the vertical columns. All beams in the structure are A36 structural steel. The length of the beam between two welded end plates is 11.896 feet. The horizontal beam was fixed on both ends by identical bolted connections, with eight bolts per plate as shown below in Figures 1a and 1b.

Figure 1a: View of West side of connection

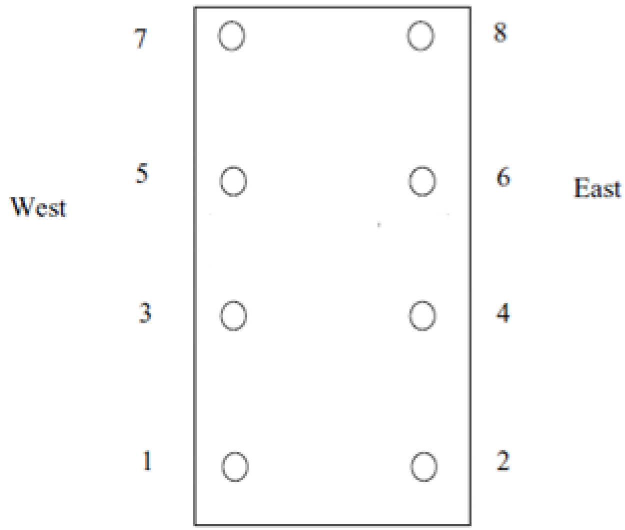

Figure 1b: End view of connection plate showing bolt locations

Bolts were SAE Grade 5, 0.75 inches in diameter and 2.83 inches long (nominal). Bolts were tightened beyond the elastic limit in accordance with RCSC Specifications for structural joints using ASTM A325 or A490 Bolts (Research Council on Structural Connections, 2004).

Impact was from a one-pound claw hammer swung by hand, striking a point at a quarter-span distance from the joint under analysis. Measurements were taken proximal to the joint, by placing the listening piece of an electronic stethoscope on the top of the horizontal beam, and also on the side of the vertical support column. The listening piece was held with firm and consistent pressure against the metal surface. Measurements were taken with the bolted joint in twenty-six configurations varying from fully tight (all eight bolts tight) to four bolts loose and four bolts finger tight. Records were processed using Audacity ® acoustic processing software, which could be downloaded at no cost at the time of this study (Audicity® v. 2.0.6, 2014).

The listening device was a Rhythm ds32a Digital Stethoscope, from Thinklabs, Inc, (Thinklabs, Inc., 2014). The stethoscope placed at the horizontal measurement location is shown in Figure 2.

Figure 2: Stethoscope and placement at horizontal measurement location

The Rhythm ds32a is an electronic stethoscope that filters and records acoustic data when applied and activated. The listening piece incorporates a flexible material that is placed in contact with the surface. The back of the flexible material moves in an electric field within the listening piece, creating a measurable electric signal that is further processed by the stethoscope to closely simulate the response of a common analog stethoscope. Like an analog stethoscope, the frequency response of the Rhythm ds32a can be "tuned" to be more sensitive to lower frequencies by increasing the pressure against the surface (Finkelstein, 2008); however, this tuning property has virtually no effect in the Rhythm ds32a beyond 1000 Hz (Thinklabs One, 2014). Firm pressure was used to ensure good acoustic coupling with the steel surface.

Measurements were recorded for a total of 26 different combinations of loose, finger tight, and tight bolt conditions. Records were not referenced in any manner to the input signal. Data were recorded on a laptop computer and post-processed using Audacity ® acoustic processing software[8]. The sampling rate was 44 KHz, and a Hanning window was used. Data records were trimmed and spectrograms were created for each record.

Two records were enhanced by applying the notch filter shown in Figure 3.

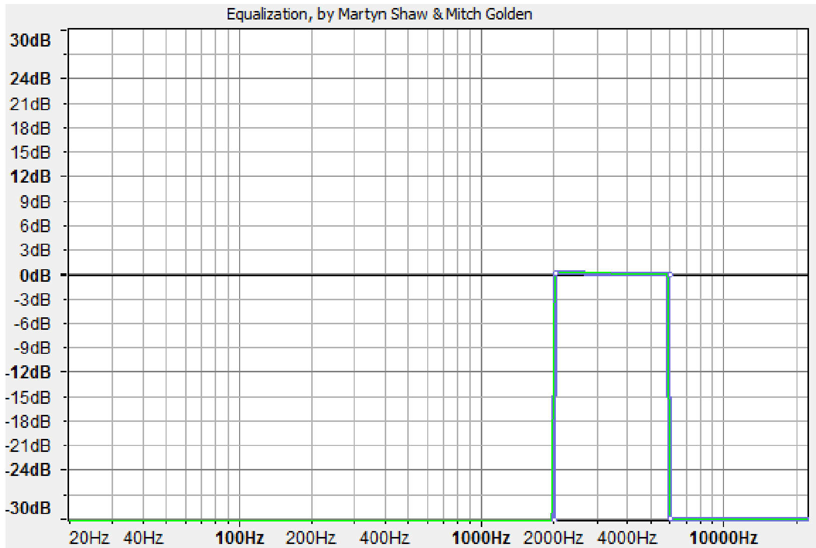

Figure 3: Notch filter applied to two cases (figures 16 and 17)

Results

The end conditions of the beam were surmised to vary between clamped on both ends to pinned and clamped as the bolts were loosened. Table 1 shows the natural frequencies associated with the first six modes for both end conditions, calculated after the method presented in Blevins (Blevins, 1979) .

Mode Number	Natural Frequency (Hz), Both ends clamped	Natural Frequency (Hz), Pinned-Clamped End Conditions
1	373	257
2	1028	837
3	2015	1737
4	3331	2971
5	4975	4533
6	6949	6425

Table 1: Natural Frequencies of first six modes, clamped-clamped and pinned clamped ends

Spectrograms associated with the "all bolts tight" condition and the "all bolts finger tight" condition are shown below in Figures 4 through 15. The time axis (seconds) is shown on the top of every plot, and the frequency axis (Hz) is shown on the side of every plot. Data acquired from the vertical sensor location did not provide significant information beyond data acquired from the horizontal sensor location; therefore, only spectrograms from the horizontal sensor location are presented.

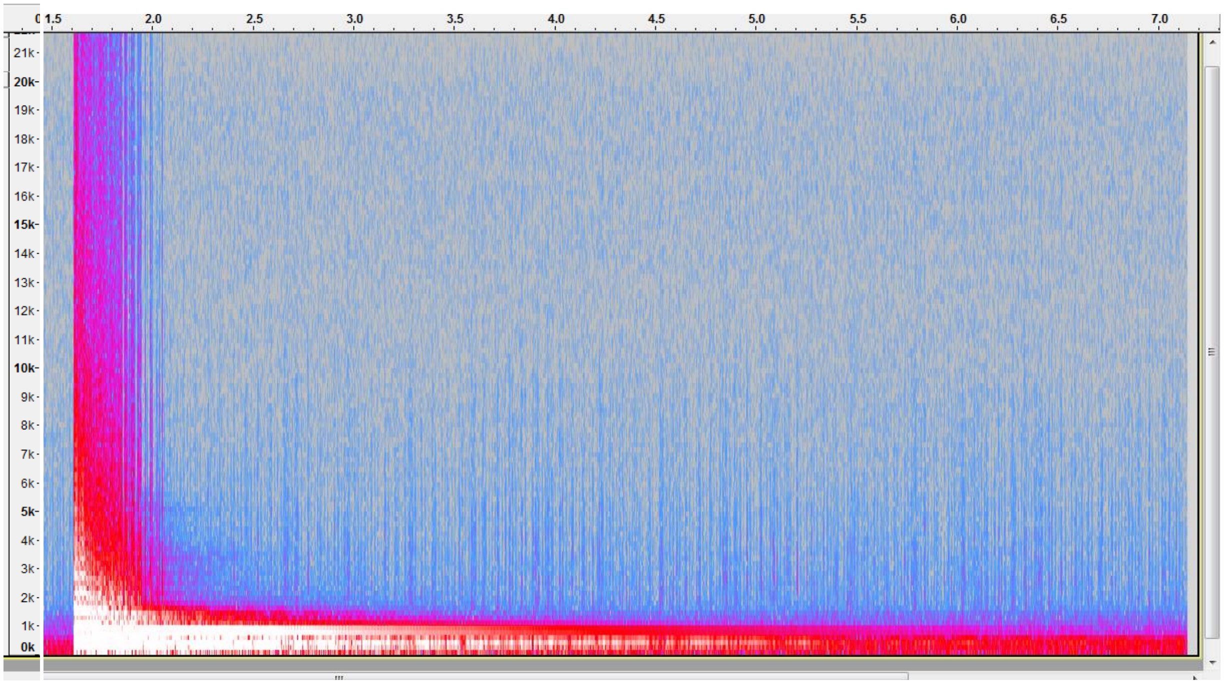

Figure 4: Spectrogram for all bolts tight, horizontal beam location, broad time base

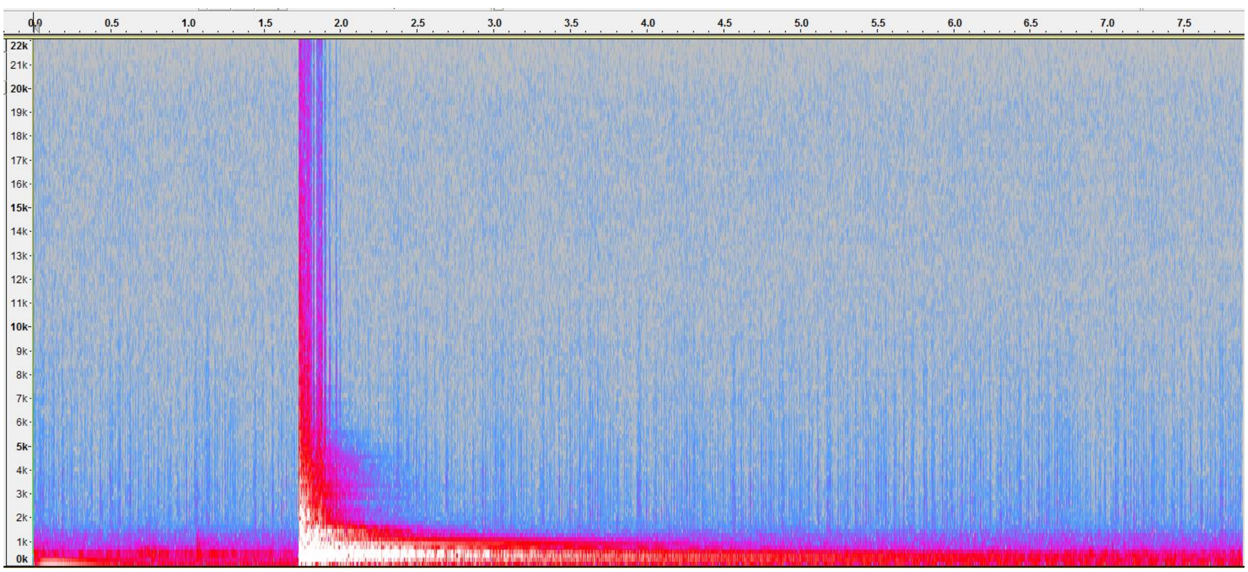

Figure 5: Spectrogram for all bolts finger tight, horizontal beam location, broad time base

The plots shown in Figures 6 through 15 have time bases narrowed to the neighborhood of the impulse in order to elucidate the differences between spectra.

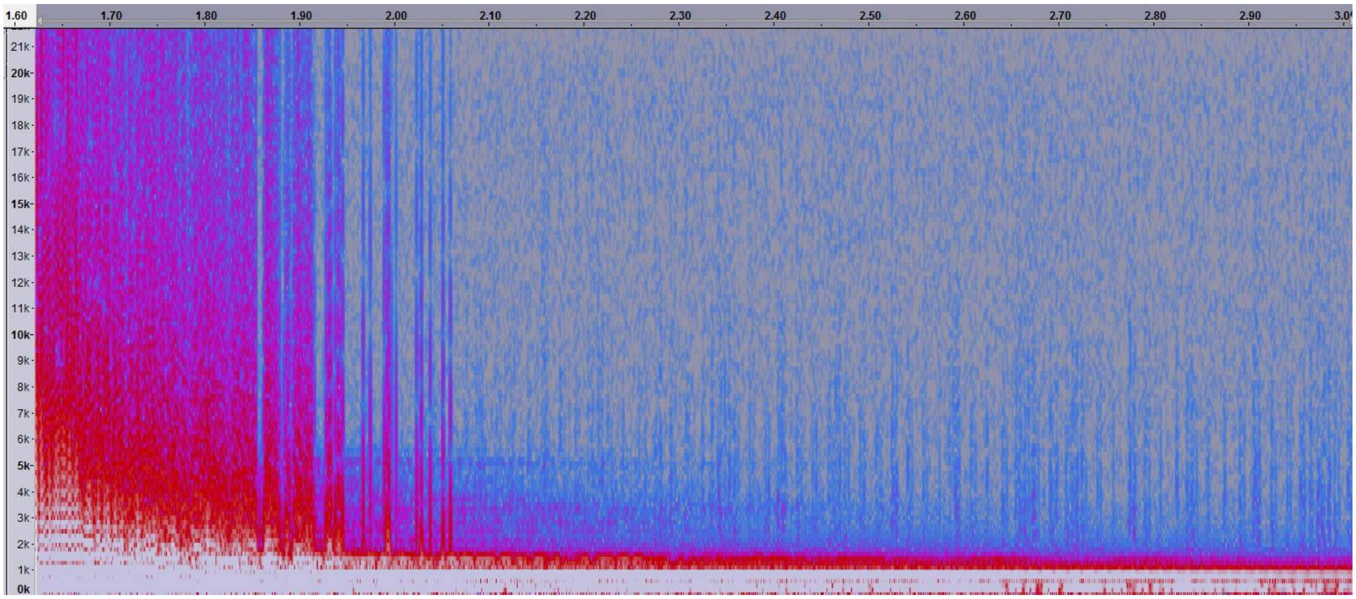

Figure 6: Spectrograms for all bolts tight, horizontal beam location, narrow time base

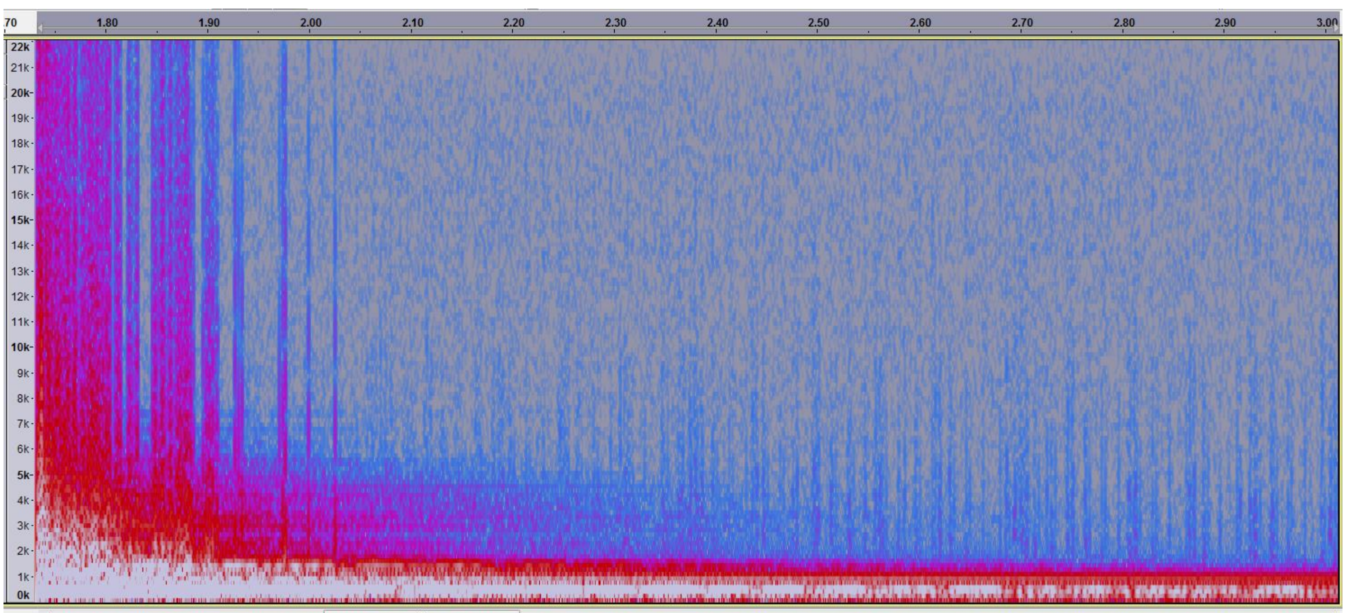

Figure 7: Spectrogram for all bolts finger tight, horizontal beam location, narrow time base

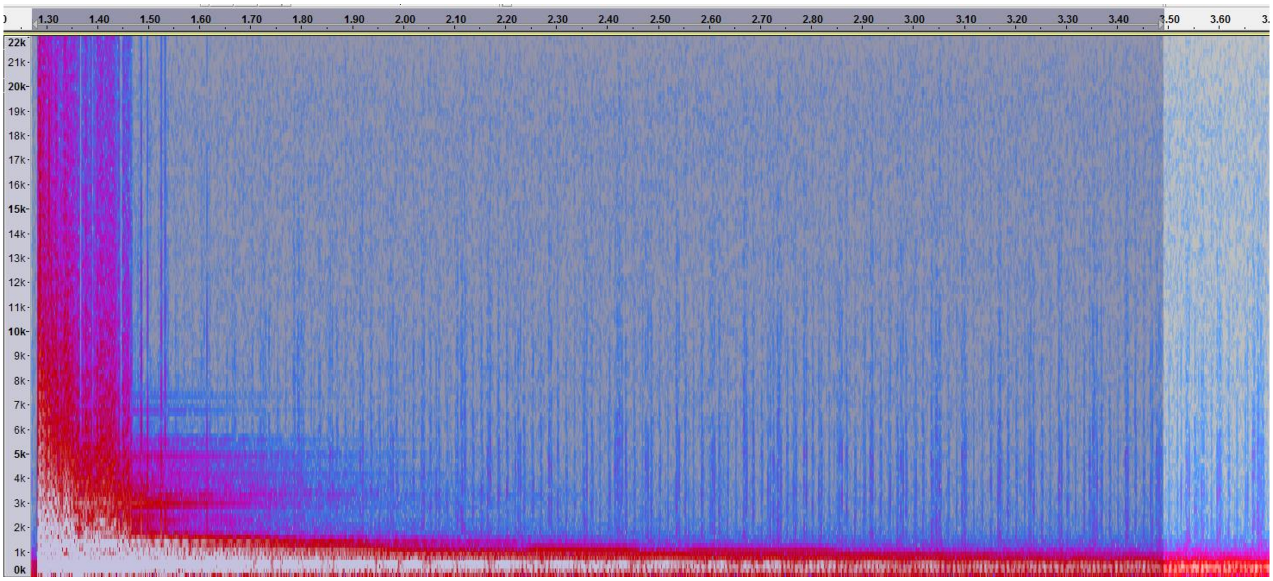

Figure 8: Spectrogram for bolts 1278 loose, 3456 finger tight, horizontal beam location (narrow time base)

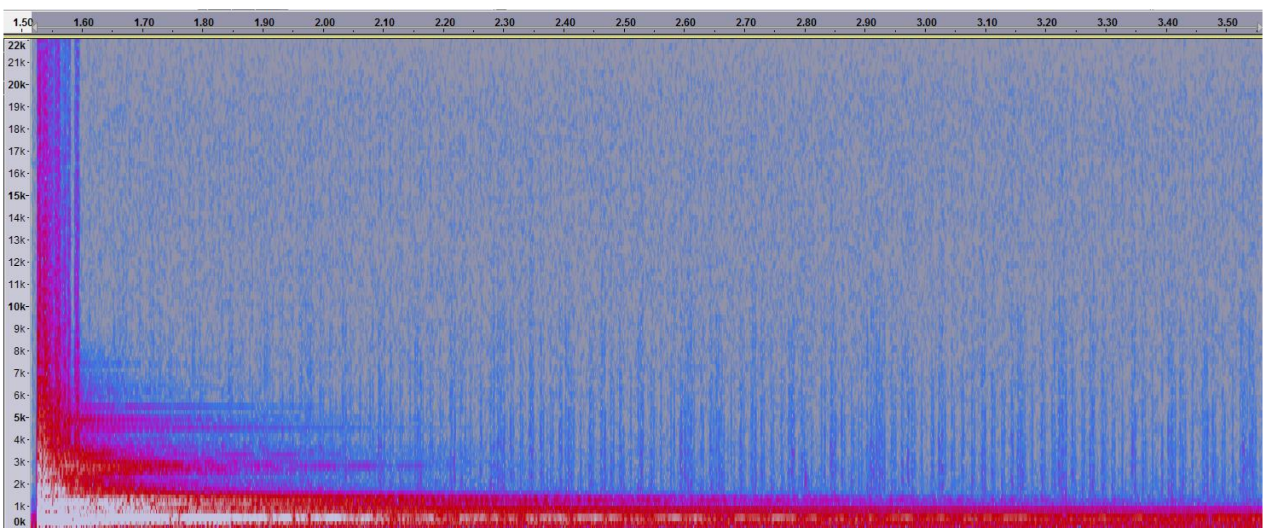

Figure 9: Spectrogram for bolts 3456 loose, horizontal beam location (narrow time base)

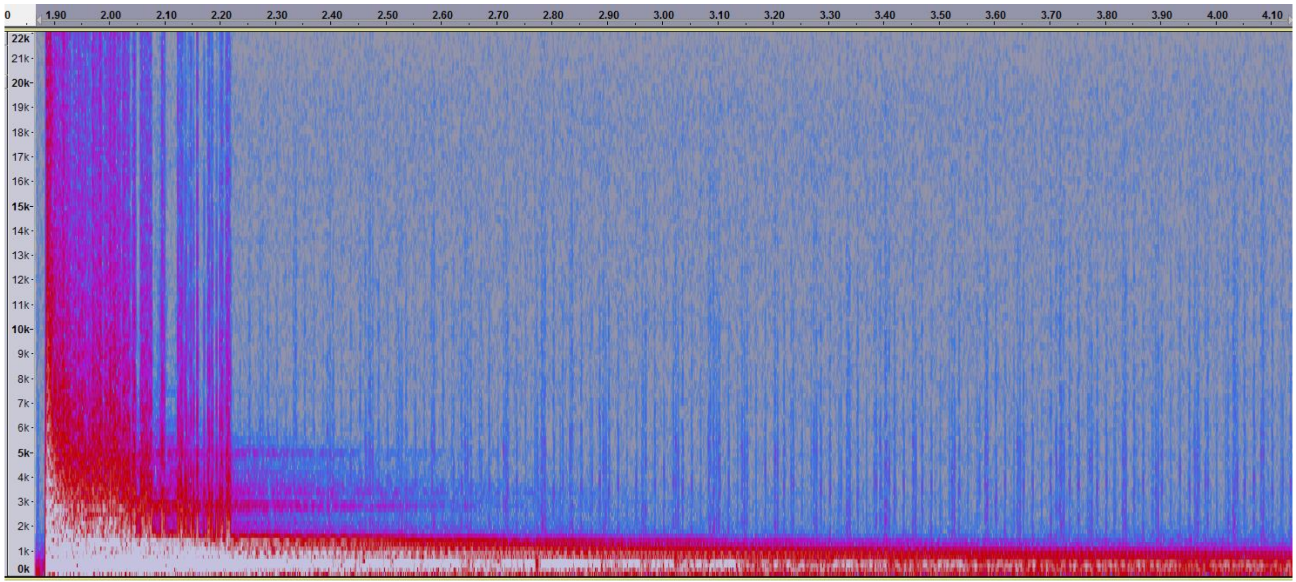

Figure 10: Spectrogram for bolts 56 loose, horizontal beam location (narrow time base)

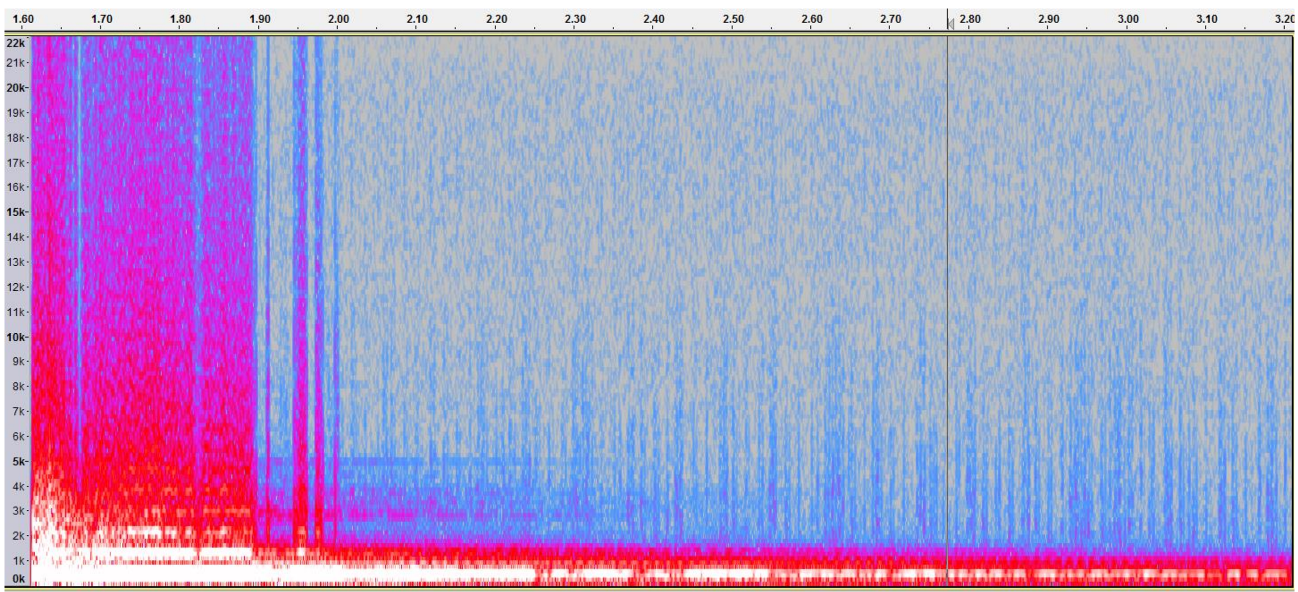

Figure 11: Spectrogram for bolt 5 loose, horizontal beam location (narrow time base)

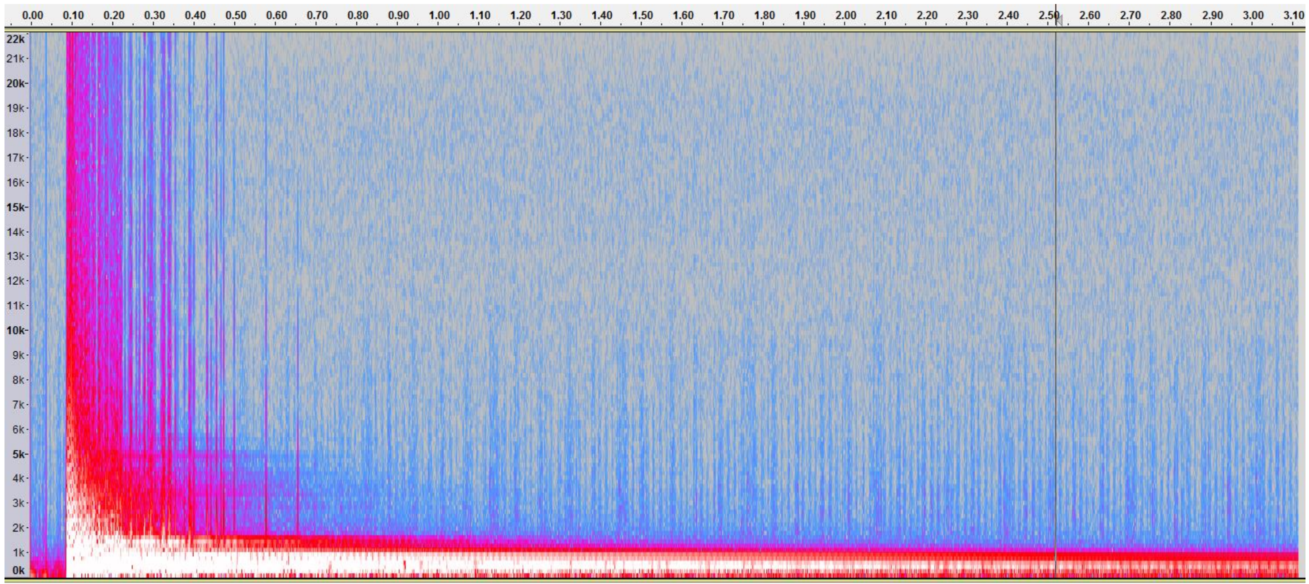

Figure 12: Spectrogram for bolt 1 loose, bolts 345678 finger tight horizontal beam location (narrow time base)

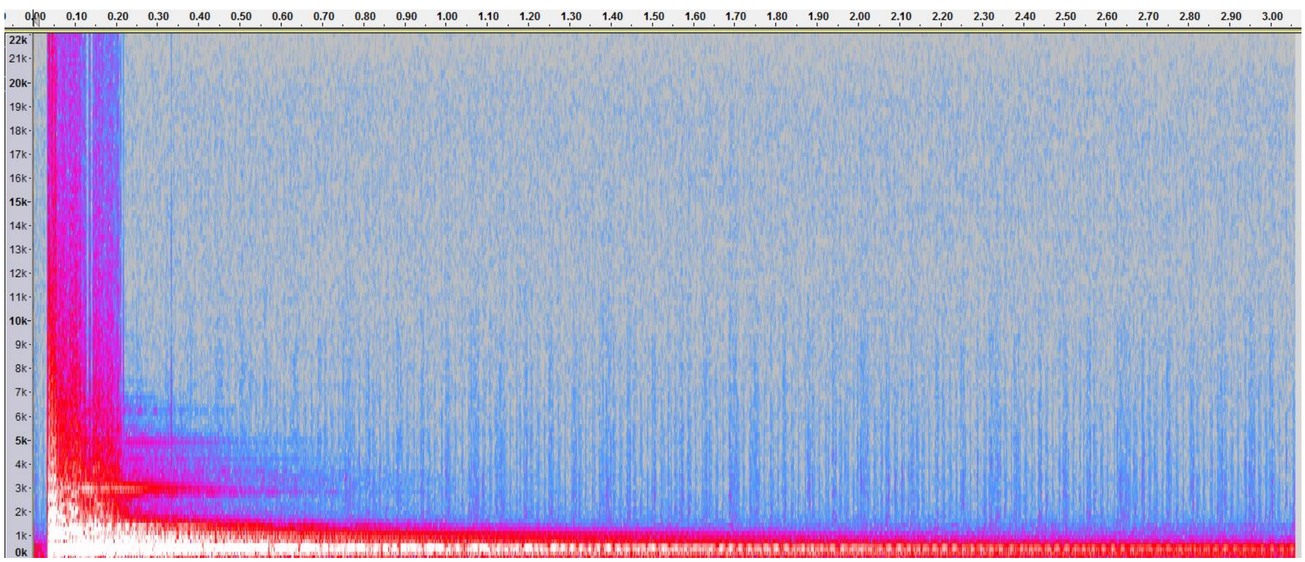

Figure 13: Spectrogram for bolts 127 loose, bolts 34568 finger tight horizontal beam location (narrow time base)

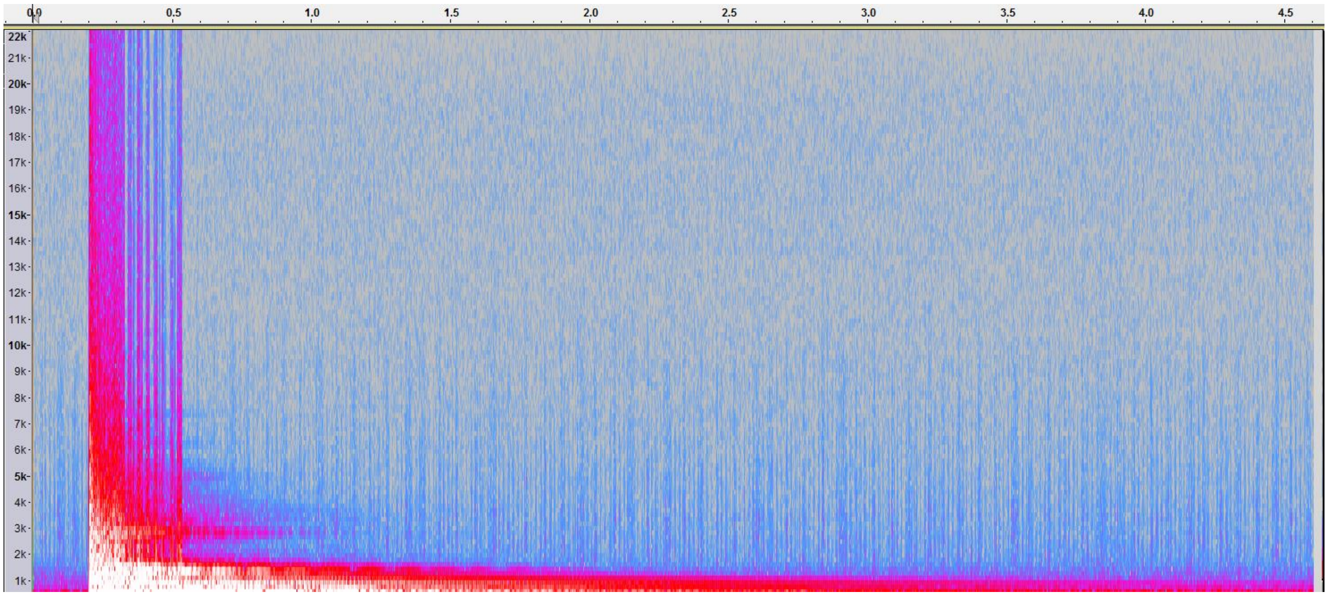

Figure 14: Spectrogram for bolts 56 finger tight horizontal beam location (narrow time base)

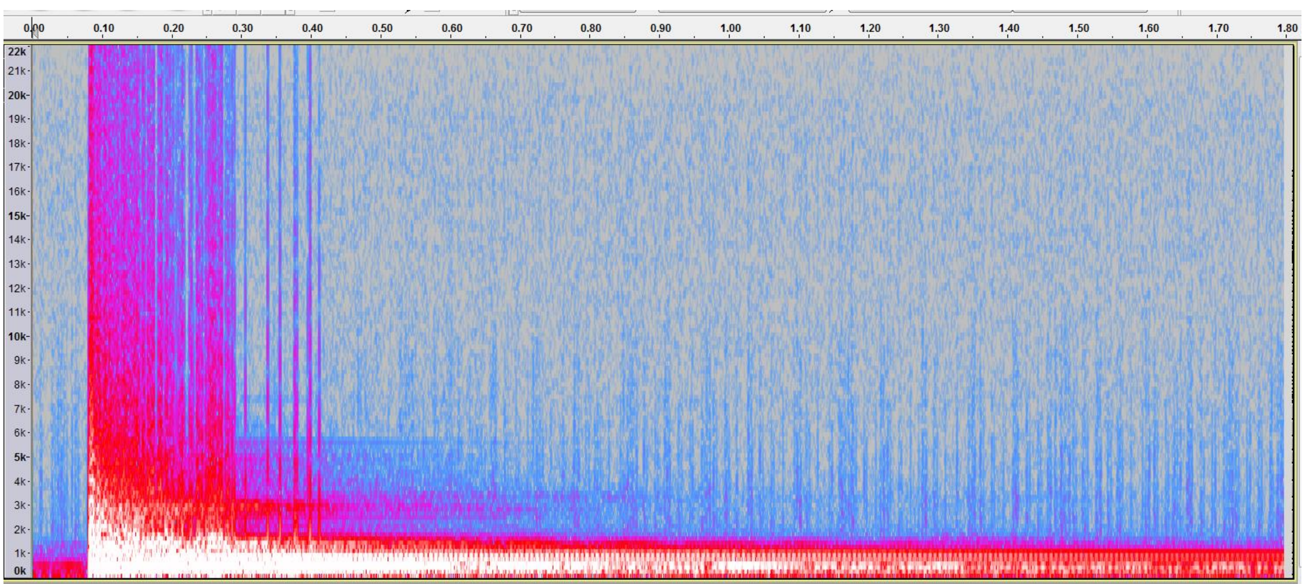

Figure 15: Spectrogram for bolt 5 finger tight horizontal beam location (narrow time base)

Results showed that the modes associated with the highest amplitude and longest duration appeared near or below 2000 Hz for all cases, which is the approximate upper bound for the first three modes of both end conditions. These results are expected; however, they provide no readily-apparent diagnostic information.

Higher-order modes in the regions of 3000 Hz and 5000 Hz may provide us with the ability to detect a connection that has even one bolt that is not fully tight. The mode in the region of 3000 Hz in particular was more intense and persistent in every case as the bolts were loosened.

The mode in the region of 3000 Hz is evanescent, as expected of higher-order modes, but while it persists, it is the most dominant higher-order mode in all records associated with bolts that are not fully tight.

The simple notch filter shown in Figure 3 was applied to the record from the all-bolts tight condition and to the record from the bolts 3456 loose condition. The filtered spectra are shown in Figures 16 and 17. The dominant mode in the 3000 Hz region is clearly present in the record associated with loose bolts. Audio signals from the two filtered spectra (heavily attenuated to avoid hearing damage) were noticeably and markedly different.

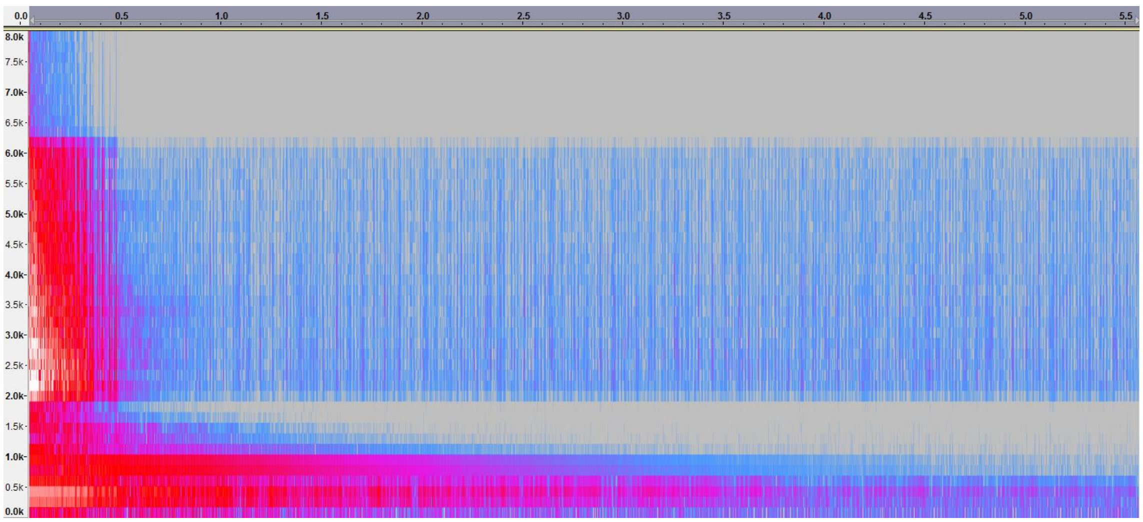

Figure 16: Spectrogram for all bolts tight, horizontal beam location, notch filtered

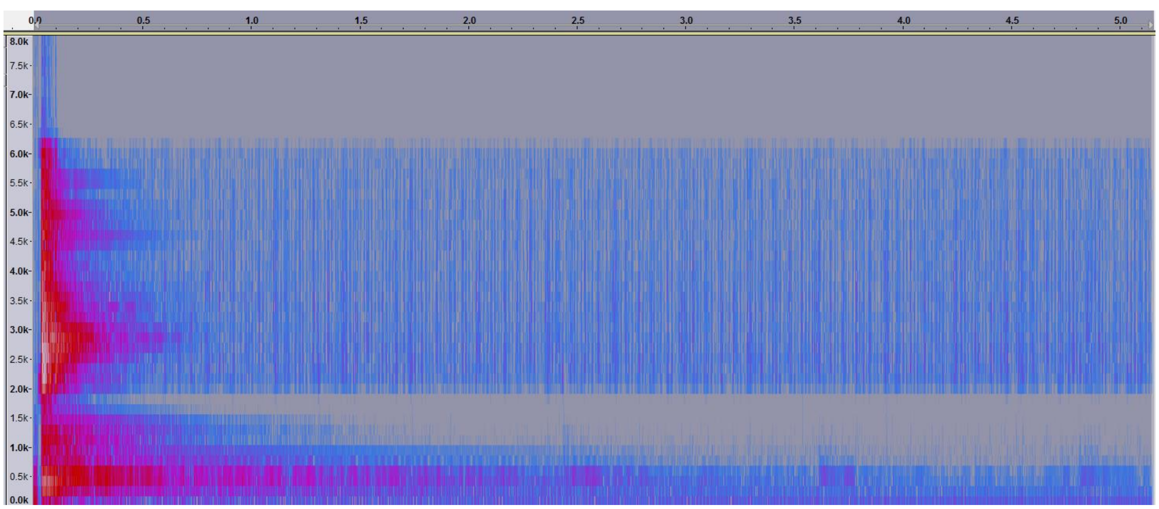

Figure 17: Spectrogram for bolts 3456 loose, horizontal beam location, notch filtered

The mode shape for a pinned-clamped beam closest to 3000 Hz was calculated using the equation provided in Blevins (1979) and plotted below in Figure 18.

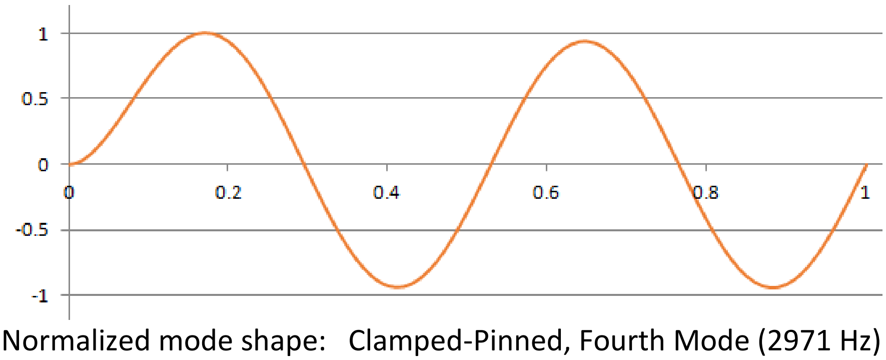

Figure 18: Normalized shape of the fourth mode for clamped-pinned end conditions

The fourth mode has considerable rotation at the pinned end which may account for the dramatic changes observed when bolts are loosened or made finger tight.

Conclusions

Results support the concept of a simple, impact-based method for identifying loose bolts in a bolted connection. However, the method presented in this paper is not specific in terms of quantifying damage. With only minimal post-processing, an audio record can be created to enhance the diagnostic value of the method. The fourth mode of the pinned-clamped beam will be investigated in future work by applying the method presented in this paper to beams of different lengths and sizes and thus, different natural frequencies associated with the fourth mode of vibration. Future work will also explore the possibility of quantifying the acoustic-based assessment process presented in this paper for structural health monitoring.

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