Indications of Vibratory Stress Relief in New Guitars

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Abstract—This paper presents frequency response measurements from new acoustic guitars before and after a 168-hour exposure to broadband vibration. The data shows changes consistent with that observed and used to indicate effective vibratory stress relief in other applications. These changes occur around the natural frequencies of the response peaks and include increases in magnitude of the peaks and shifts in the peaks to lower frequencies. In addition to presenting this data, a goal of this paper is to increase awareness of the physical mechanisms associated with these changes by referencing and briefly describing the relevant literature.

I. INTRODUCTION AND BACKGROUND

Residual stress is the stress in a component or structure that remains after the original source of the stress is removed. It occurs in manufacturing from processes such as forming, bending, welding and machining [1]. It occurs naturally in the wood of a growing tree and in wood that is drying or formed into a structure or instrument.

Commonly known effects of residual stress include distortion of component shape, formation of cracks, and reduced fatigue life. Less known effects of residual stress include increased stiffness [2] and internal friction [3].

There exist a number of methods for measuring residual stress [1]. Relaxation measurement methods are generally destructive and involve cutting or removing material to release residual stress while observing deformation. Diffraction methods are nondestructive and are based on using electromagnetic radiation, such as X-rays, to measure the distance between atomic planes, which is related to the stress in a component.

A traditional technique to reduce residual stress in components and structures is to apply a thermal process [4], [5]. This is known as thermal stress relief (TSR) and requires an oven or furnace large enough for the structure with residual stress to be treated.

Another technique uses cyclic loading to reduce residual stress in components through application of vibration [5], [6]. This is known as vibratory stress relief (VSR) and usually involves attaching a vibrator to a structure to be treated and vibrating the structure over a range of frequencies. The vibrator often used for this purpose is an unbalance vibratory motor which is driven over a range of rpm values to vibrate the structure with particular emphasis at the natural frequencies.

A number of studies [6] – [8] have correlated the effectiveness of VSR treatment in reducing residual stress with changes in the vibration response of the system treated. These changes occur around the natural frequencies where the response peaks, and include increases in magnitude of the peaks, shifts in the peaks to lower frequencies, and narrowing of the peaks.

Klauba and Adams [7] present typical vibration data as a function of frequency (in terms of unbalance vibratory motor rpm) from an effective VSR treatment performed on a structure. Most of the peaks in this vibration response data show the changes that have been correlated to reduced residual stress.

The physical basis for such changes in response are not widely appreciated but have been provided in the literature. For example, the shift in the vibration response peaks to lower frequencies due to reduction in residual stress would seem to require a reduction in stiffness with reduction in residual stress. This cannot be explained with linear elastic mechanics. However, Shi et al [2] have shown that residual stress directly contributes to bending stiffness in a cantilever beam when the geometrical nonlinearity of deformation and the bending moment after deformation are taken into account.

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In addition, the increase in magnitude and narrowing of the vibration response peaks would seem to require a reduction in internal friction or damping with reduction in residual stress. Lai et al [3] studied vibration induced crystal lattice movements associated with internal friction. At moderate applied vibration levels, the internal friction was found to decrease in time with residual stress relief. At vibration levels high enough to cause fatigue crack nucleation, the internal friction was found to increase with time and fracturing due to fatigue.

The origin of this paper is the result of the author recently making a connection between changes in a typical effective VSR treatment [6] – [8] with data that the author had previously collected while assessing the effect of extended vibration exposure applied to new Martin D-28 acoustic guitars. This previously collected data was never published. However, after recently learning about the changes in vibration response of systems subjected to VSR treatment, the author recalled similar changes in the guitar vibration response data and felt compelled to publish the data and potential connection with VSR. This paper presents vibration frequency response data of new Martin D-28 guitars before and after broadband vibration exposure that exhibit the same type of changes in vibration response of effective VSR treatments.

Photo 1 – Guitars suspended in acoustic-vibration box.

II. Test Instruments and Vibration Exposure

Two new Martin D-28 acoustic guitars supplied by the manufacturer are used as test guitars in this study. Although the serial numbers for these instruments are available, these are referenced as test instrument A and test instrument B in this paper.

Photo 2 – Guitars suspended on elastic bands for impact testing.

The guitars are suspended at the neck in a box constructed of medium density fiberboard as shown in **Photo 1**. Padding is used to protect the contacting surfaces at the neck. Vibration excitation is provided with noncontact, broadband sound waves driven within the box using a high-power audio system. The audio input is broadband pink noise in the frequency range of 20 to 20,000 Hz and the measured sound level within the box is 129 dB. Both guitars are subjected to this acoustic-vibration for a period of 1 week or 168 hours.

III. Frequency Response Measurements

The vibratory response of the guitars is assessed before and after the vibration exposure using modal impact testing. For this test, the guitars are kept in precise standard tuning and are suspended on elastic bands at the neck under the nut and at the end pin as shown in **Photo 2**. The impact is applied on the bass side of the bridge with a small PCB model 086D80 impact hammer with a vinyl tip and a sensitivity of 59.5 N/V. This provides uniform excitation up to 1,000 Hz. A spring and positioning guide, shown in **Photo 3**, are used to provide repeatable hammer hits.

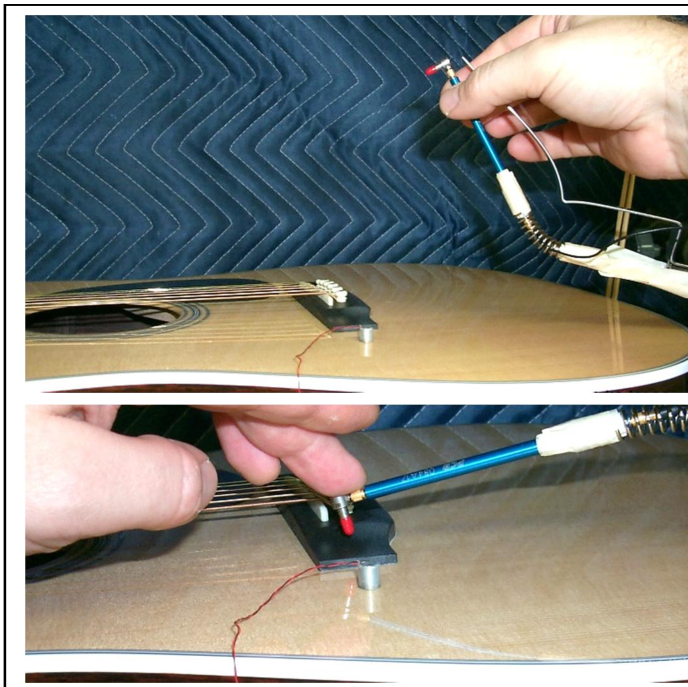

Photo 3 – Impact hammer release position and impact location.

The impact response vibration of the guitars is measured with a PCB model 309A accelerometer placed at two different positions as shown in **Photo 4**: (a) on the bass or left side of the bridge (one inch from the bridge), and (b) at the center (one inch from the bridge). The sensitivity of the accelerometer is 200 g/V. It is attached with bees wax which is easily removed and does not damage the guitar finish.

In these tests, the frequency response is defined with the impact force *F* (in units of Newtons, N) to the instrument as the input and the resulting vibratory acceleration *A* (in units of g) of the instrument sound board as the output or response. It is calculated using a two-channel dynamic signal analyzer as follows. Time trace measurements of the dynamic input force *F(t)* and acceleration response *A(t)* are obtained, these measurements are windowed, and the fast Fourier transforms of these windowed time traces are computed as *F(f)* and *A(f)*, respectively. This is repeated four times, and the average power spectra for the force $P_{FF}(f)$ and acceleration $P_{AA}(f)$, and cross spectra $P_{FA}(f)$ are computed as

$$
\begin{aligned}
P_{FF}(f) &= \frac{1}{n}\sum F(f)F(f)^* \\
P_{AA}(f) &= \frac{1}{n}\sum A(f)A(f)^* \\
P_{AF}(f) &= \frac{1}{n}\sum F(f)A(f)^*
\end{aligned}
\qquad (1)
$$

Photo 4 – Accelerometer positions left of bridge and center.

where * indicates complex conjugate and $n = 4$. The frequency response is then computed as

$$
FR(f) = \frac{P_{AF}(f)}{P_{FF}(f)} \qquad (2)
$$

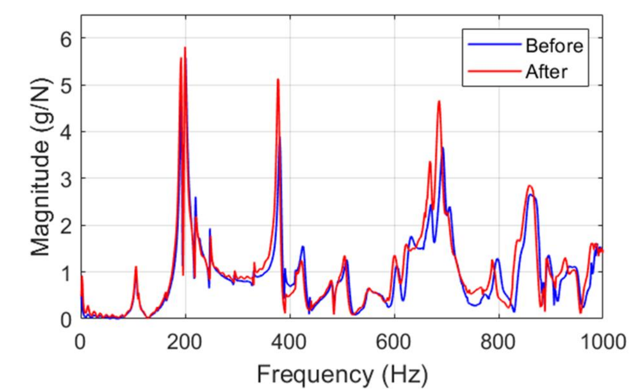

Figure 1 – Test instrument A, center accelerometer position, before and after 168-hour vibration exposure.

The vibratory response is presented as the magnitude of this frequency response with units of acceleration response per unit force input, i.e., g/N. Coherence is also computed to assess the validity of the measurement. Coherence provides a measure of the power in the test instrument vibration that is caused by the power in the impact force. A coherence of 1 means that all of the vibratory acceleration is caused by the impact force, whereas a coherence of 0 means that none of the vibration is caused by the force. The coherence $\gamma^2(f)$ is a function of frequency and is computed as

$$
\gamma^2(f) = \frac{P_{AF}(f)\, P_{AF}(f)^*}{P_{FF}(f)\, P_{AA}(f)} \qquad (3)
$$

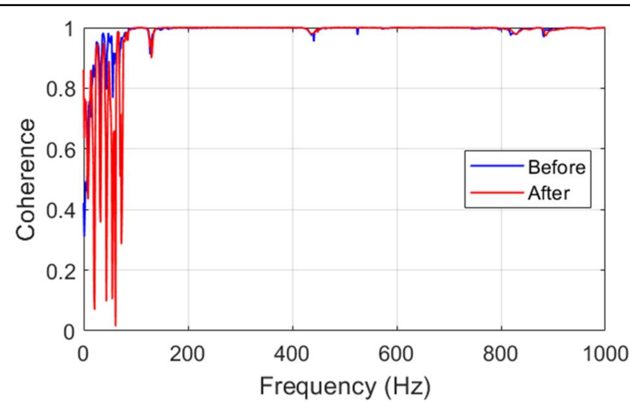

Figure 2 – Coherence before and after 168-hour vibration.

The frequency response data for test instrument A with the accelerometer placed at the center position is presented in Figure 1. This shows several natural frequencies of the guitar as expected in the 0 to 1,000 Hz frequency range. Figure 2 shows the corresponding coherence for this data. The coherence is one or close to one around the peaks and over most of the frequency range. The coherence is low, as expected, where the response is very low; this is of no concern since the interest in this work is around the response peaks.

Figure 1 provides frequency response data before (blue) and after (red) the 168-hour vibration exposure. This comparison reveals an increase in amplitude of many of the peaks. Since the response is normalized with respect to the input, this means more response (measured acceleration) per unit input (measured impact force). Physically, this suggests a reduction in internal friction or damping. By studying vibration induced crystal lattice movements associated with internal friction, Lai et al [3] found that such a change can occur with a reduction in residual stress.

In addition, the before and after data comparison reveals a decrease in frequency of several of the peaks. Physically, this suggests increased flexibility or decreased stiffness. Although this cannot be explained with linear elastic mechanics, Shi et al [2] have shown that such change can occur with reduction of residual stress when the geometrical nonlinearity of deformation and the bending moment after deformation are taken into account.

Both of these changes in response peaks are consistent with the changes observed in a typical effective vibration stress relief (VSR) treatment which at least indicates the possibility of stress relief in the new test guitars. The value in this observation is that it provides a plausible physical explanation for the increase and shift in response peaks, i.e., due to residual stress relief.

The frequency response data for the D-28 test instrument A with the accelerometer placed at the left of the bridge position is presented in Figure 3. In addition, the frequency response data for the D-28 test instrument B with the accelerometer placed at the center position and left of the bridge position are presented in Figures 4 and 5, respectively. These data show similar changes in response peaks after the 168-hour vibration exposure.

The value in this additional data is that it shows similar changes for two different accelerometer positions and for two different, but same make and model, new guitars. This at least reduces the probability that the observation is an anomaly.

These observations and connection with changes in typical effective VSR treatments, provide a possible physical explanation for the changes in response peaks, specifically, a reduction in residual stress.

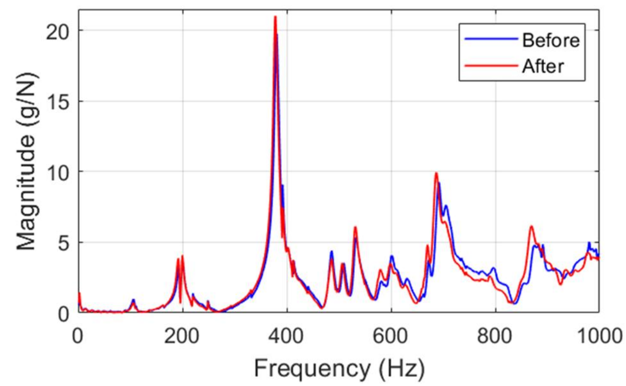

Figure 3 – Test instrument A, left accelerometer position, before and after 168-hour vibration exposure.

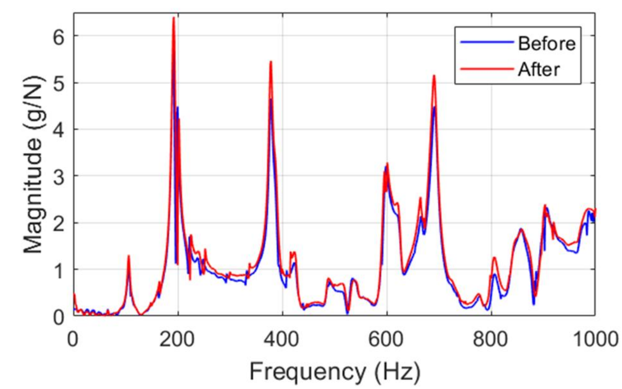

Figure 4 – Test instrument B, center accelerometer position, before and after 168-hour vibration exposure.

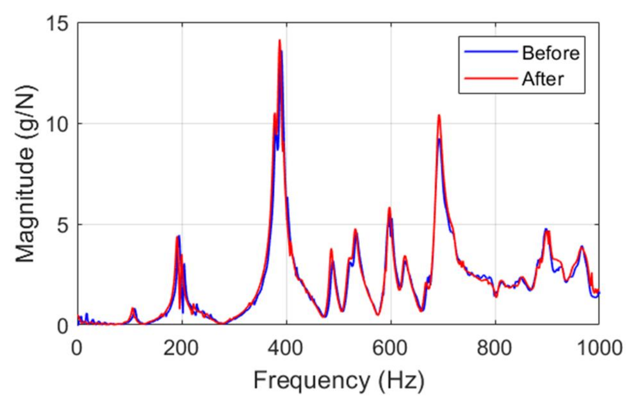

Figure 5 – Test instrument B, left accelerometer position, before and after 168-hour vibration exposure.

IV. Subjective Evaluation

In addition to the before and after frequency response assessment, a blind evaluation of the test instruments and two additional new control instruments of the same make and model was performed by four participants. The test guitars were mostly preferred over the control instruments by the participants and perceived as being “more open”. This is not an uncommon description used by guitarists or violinist, for that matter, to describe an instrument. Perhaps, this is descriptive of the change one perceives when an instrument experiences a reduction in residual stress.

V. Conclusion

This paper presented frequency response data before and after 168-hours of 129dB level noncontact acoustic induced vibration exposure on two new D-28 Martin guitars. Changes in many of the vibration response peaks were found for both test guitars in measurements from two locations on each guitar. These changes include increases in magnitude of the peaks and shifts in the peaks to lower frequencies which are used as indicators of effective stress relief in vibratory stress relief (VSR) treatment of components and structures.

References and a brief description of work that provide a physical basis for shifts in the vibration response peaks to lower frequencies and increase in magnitude of vibration response peaks from exposure to vibration and stress relief are provided. Namely, the shift in peak response frequencies requires taking into account geometrical nonlinearity of deformation and the bending moment after deformation associated with reduction of residual stress. And the increase in peak response magnitude requires a close look at vibration induced crystal lattice movements associated with internal friction.

VI. Acknowledgments

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VII. Bibliography

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