Response Variation in a Group of Acoustic Guitars

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Dynamic testing was performed on a pool of guitars in the production facility of a major guitar manufacturer. The production process is highly automated, with the goal of improving quality and reducing build variation. However, no objective metric has yet been used to quantify the differences in the dynamic response of the instruments. We performed dynamic testing on the assembly line to measure the lower resonant frequencies of a pool of instruments. The standard deviations of the first two modes were a few percent of the mean, and the data suggest that a significant percentage of the variation is due to intentional differences in the species used for backs and sides.

It is commonly accepted in manufacturing operations that build variation is inversely related to build quality. Efforts to improve the product and the manufacturing process are hampered if the effect of changes cannot be distinguished from build variation. So it is critical that good metrics for build variation are established. In guitar manufacturing, dimensions of components and completed instruments are routinely measured as part of the production process. Dimensions are certainly useful descriptors but are not directly related to the sound produced by the instruments. A better metric would be more directly related to the physical mechanisms that produce sound.

The structural-acoustic interaction through which an instrument makes sound is strongly conditioned by the coupled resonant frequencies of the instrument. Thus, controlling variation in those frequencies is key to controlling variation in the tonal quality. Ideally, a measurement that relates dynamic response of the instrument to radiated sound could be used; an intriguing possibility is radiation efficiency, but current methods take far too much time and equipment to be practical in a production environment. Near-field acoustic holography is faster but is too expensive to be practical.

A practical first step toward a more global metric is to use the lower resonant frequencies of the instruments. It is generally accepted that the lower frequencies strongly condition the sound and exhibit structural-acoustic coupling in a way that can be described by simple math models. Furthermore, these frequencies can be measured quickly using inexpensive equipment. A well-controlled build process should manifest itself in low variation in the lower coupled resonant frequencies.

Resonant frequencies were measured on a pool of instruments during the assembly process at Taylor Guitars in El Cajon, CA (www.taylorguitars.com). Most of the instruments had completed and finished bodies but no necks. It was desirable for body structure to be complete, including the finish. However, since the neck installation involves hand fitting, it was important to be 'upstream' of that process. If build variation were large for the bodies, it would be necessary to move to earlier stages of the build process to identify the source. If the variation were small, testing could be conducted after final assembly.

Taylor produces a range of different instruments in the same facility (Figure 1), and all instruments available at that stage of assembly were tested, regardless of the model. The data presented here are from a single design, called a Grand Auditorium Cutaway. There are various build levels for this design, but the differences are limited to the side and back materials and complexity of the trim. The basic design of the instrument is shown in Figure 2. All instruments had the same dimensions, the same bracing, the same bridge and the same soundboard material.

Based on a paper presented at IMAC XXV, the 25th International Modal Analysis Conference, Orlando, FL, February 2007.

Figure 1. Collection of guitars from Taylor product line.

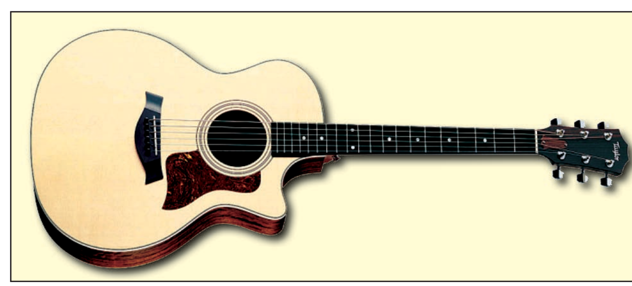

Figure 2. Grand auditorium cut-away, Model 414CE. (Courtesy Taylor guitars.)

Manufacturing Process

The guitar manufacturing process is far removed from the romantic notion of the skilled craftsman sitting at a bench and creating instruments by hand. A modern guitar factory uses the same automated processes found in other large-scale production operations, and many employees are closer to being machinists or machine operators than to being luthiers. If there is a facet of guitar making that sets it apart from other products it is the variable nature of the raw materials. High-quality guitars are generally made from solid wood (little or no plywood) that is sawn from selected logs. These logs are chosen to be free of knots, checks or other defects and generally have straight grain with closely spaced growth rings. The exception is 'figured' wood, where waves in the grain result in an attractive, almost luminescent, pattern in the finished instrument. Tops are made almost exclusively from Spruce, Cedar and Redwood. Traditionally, sides and backs are made from Mahogany, Rosewood or Maple. However, the supplies of these woods have been depleted and many manufacturers now use a wide range of tropical hardwoods such as Ovangkol, Sapele, Cocobolo, Bubinga and Koa. Variation is introduced into the build process not only through the inherent variability of wood, but also through introducing different species with different mechanical properties.[1,2]

The wood used for instruments, no matter the species, has generally been carefully selected from a large pool of lumber. Many manufacturers also have a skilled luthier do a subjective evaluation at the beginning of the build process. Typically, the blanks are flexed and tapped by hand to determine suitability.

Figure 3. Stacked top and back blanks being conditioned before use.

While this would seem to add significant variability to the process, my own observations and conversations with manufacturers suggest that a group of skilled luthiers will generally agree on grading a pool of instrument wood. The result is that the pool of materials going into a well-controlled build process can be assumed to be more uniform than a randomly selected sample. This uniformity probably doesn't rise to anything like the level of processed materials such as metal or plastic, so response variation is assumed here to be partially due to material variation and partially due to variations in the build process.

Since unfinished wood absorbs moisture from the atmosphere, all wood is conditioned for several weeks before being introduced into the building process. The moisture content changes slowly – over days or weeks rather than hours. Thin slabs are stacked with spacers (Figure 3) and left in an open area before being cut into components. Blanks are then taken to a climate-controlled room where they are cut into tops and backs.

Most of the production process uses computer-controlled equipment. Tops and backs are cut using lasers and sanded to an even thickness. Necks and headstocks are formed using CNC mills (Figure 4), and even the finish is applied using an industrial robot and then buffed using another robot (Figure 5). There are still a few hand processes, though they largely involve decorative aspects of the instrument. Figure 6 shows the sound hole decoration being applied by hand. Note that the individual pieces are cut out using a computer-controlled laser, and only the actual installation is done by hand.

Figure 7 shows instruments after being finished, but before bridges are installed and before the necks are fitted. Note that there are several different models on the cart, and they are made from a range of different woods.

Test Method

We performed a standard hammer impact test on the instruments. The input source was a modal hammer with a hard plastic tip. The response was observed with a noncontacting laser displacement sensor (Keyence LK-G82). The sensor was placed so that the interrogation point was as close as possible to the hammer input point on the lower right side of the bridge. Figure 8 shows the test arrangement with hammer and laser sensor. Data were recorded with an Oros four-channel data acquisition unit; the frequency response functions (FRFs) were calculated with a linear average of five taps. A typical FRF is shown in Figure 9 along with the coherence and the time-domain input signal. To ensure that our test procedure could distinguish test variation from build variation, we recorded data twice for most of the instruments so that isoplots[3] could be constructed.

Figure 4. Machining a neck on large CNC mill.

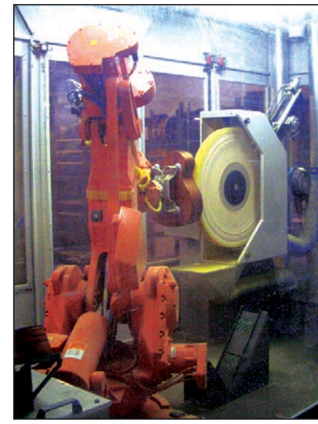

Figure 5. Industrial robot buffs guitar body.

Since four channels were available, microphones or accelerometers could have been added to the test with little change in setup time. This was rejected for two reasons. Previous testing showed that microphone data recorded in a noisy environment (like the one we used for this test) are very difficult to interpret. No quiet space was readily available, and it wasn't practical to move instruments to an acoustically quiet space. Additional accelerometers were not used, because these were production instruments that needed to be shipped after testing. There were concerns about leaving wax or tape residue on instruments whose value sometimes exceeded $2000 each.

The boundary condition is important when conducting a dynamic test like this one. After some experimentation, good results were obtained using small blocks cut from 1-inch hard felt. The blocks were placed under the instrument at the edges so they were in line with the sides and did not affect the motion of the back. It is common to support an instrument using soft foam or even rubber bands to approximate a free boundary condition. However, the

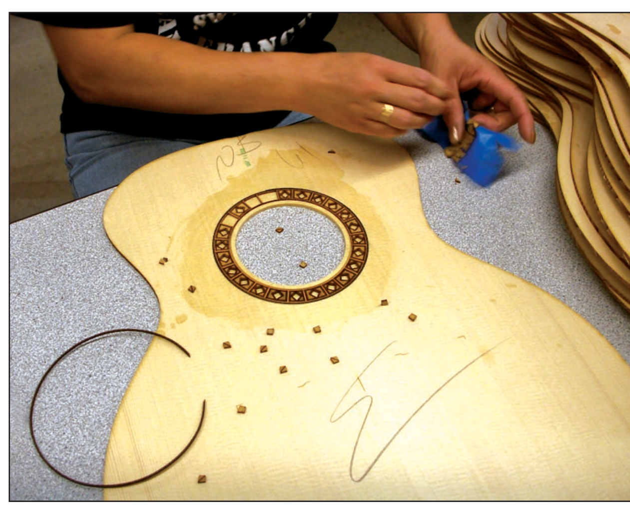

Figure 6. Applying sound-hole trim by hand.

Figure 7. Bodies and necks after finishing.

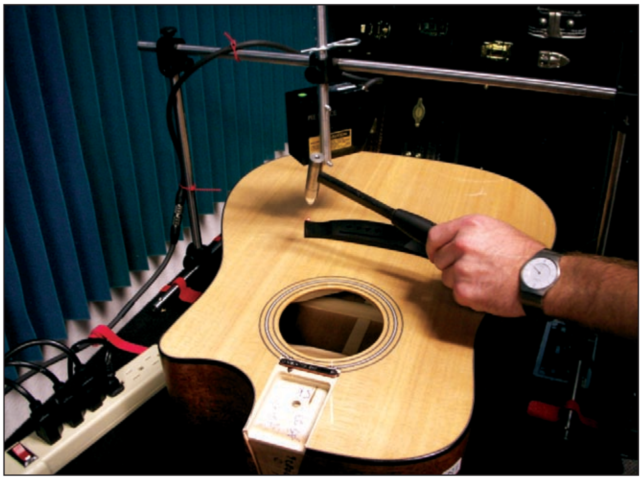

Figure 8. Testing guitar body.

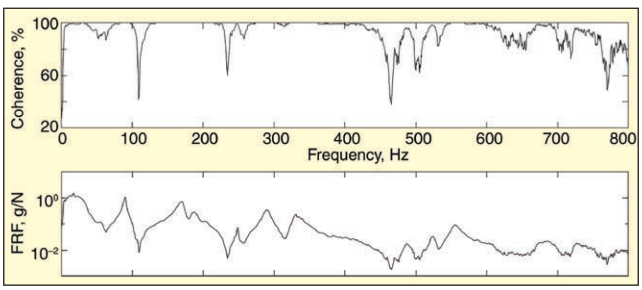

Figure 9. Typical FRF along with coherence and impact profile.

laser sensor had to be a fixed distance from the instrument, and rigid body motion that resulted from using soft supports caused the sensor to be outside its usable distance.

Test Results

After collecting frequency response functions from the different instruments, we identified the first two natural frequencies and the antiresonance that fell between them. As shown in Figure 10, the first mode of an acoustic guitar is almost always one where the top and back move out of phase with each other.[4] For this mode, there is a net change in the volume of the body and air flow through the sound hole. This is akin to the behavior of a Helmholtz resonator, and this mode is even sometimes referred to as a Helmholtz mode. However, the analogy shouldn't be pushed too far; a true Helmholtz resonator has rigid walls and a clearly defined neck surrounding the acoustic port.[5] Both of these features are missing in an acoustic guitar body.

The second mode is similar except that the top and back are moving in phase so there is less net volume change. Figure 11 shows time-averaged holograms of the first two modes of a guitar top.[6] It is clear that modes 1 and 2 (97 Hz and 205 Hz, respectively) have no internal node lines.

Figure 12 shows a typical measured FRF. The first resonant frequency is 102.5 Hz, and the second 186.2 Hz. The first antiresonance, which corresponds the first rigid body air mode,[7-9] is 127.0 Hz. At first glance, it may seem odd that an acoustic resonance frequency can be associated with an antiresonance on the FRF plot. However, the effect is analogous to that of tuned acoustic absorbers[5] as used in a wide variety of architectural and mechanical applications. This effect is widely reported and is a part of most general texts on acoustics.

Figure 13 shows the first resonant frequencies of the instruments sorted from lowest to highest. They are color coded according to the material used for the back and sides. In all cases, the tops were made from either Sitka Spruce or Engelmann Spruce, so we assume any part of the resonant frequency variation due to differences in materials is due to the back and side materials rather than top materials. The mean frequency is 100.3 Hz and the standard deviation is 2.24 Hz (2.23% of the mean frequency).

It is well established in the literature that the first resonant frequency of guitar bodies depends on both the geometry of the body and the stiffness of the sides, back and top.[4,10,11] The geometry of the body is very closely controlled during the build process. In particular, the sound hole is cut using a computer-controlled laser and is quite uniform. This feature is critical, because previous work[12] has shown that variation in sound-hole area has a large influence on the first resonance frequency. The variation in first resonant frequency is assumed to be driven by variation in material properties and by variation in the build process.

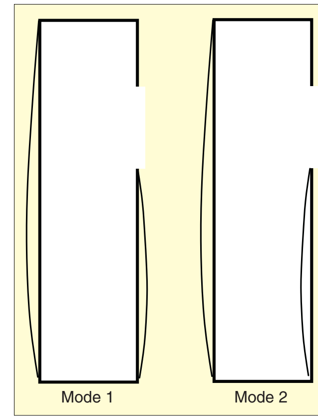

Figure 10. Lower modes of an acoustic guitar.

It is also evident that the first resonant frequency is correlated with some of the side and back materials. Sapele tends to result in lower frequencies, and Rosewood tends to result in higher frequencies. Some experienced luthiers believe that stiff sides improve the sound quality of guitars. It is interesting to note that Rosewood has been the preferred wood for guitar sides since at least the late 1800s. However, instruments made using Ovangkol exhibited no clear trend in first resonant frequency. This suggests that more careful selection of Ovangkol stock would further reduce response variation. Efforts to correlate frequency with reported mechanical properties of the different species were not successful because of wide ranges in the elastic moduli and density values.

Figure 14 shows the Helmholtz frequencies (the natural frequencies of the enclosed air volume if the sides were rigid) of the test instruments in the same order as in Figure 12. Simple mathematical models suggest that the Helmholtz frequencies should not vary between instruments since the geometry does not change. It is

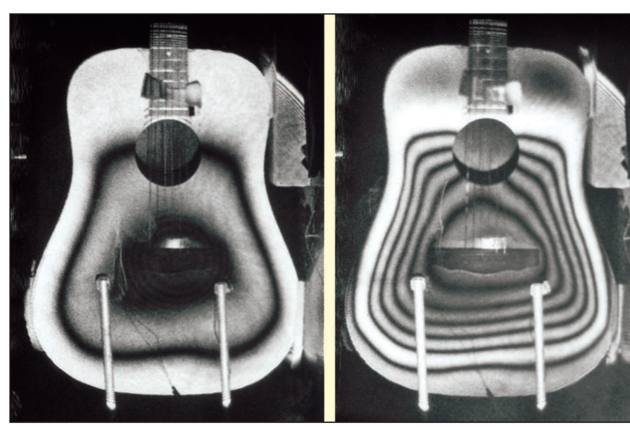

Figure 11. Time-averaged holograms of acoustic guitar top. (Courtesy Karl Stetson Associates LLC, www.holofringe.com.)

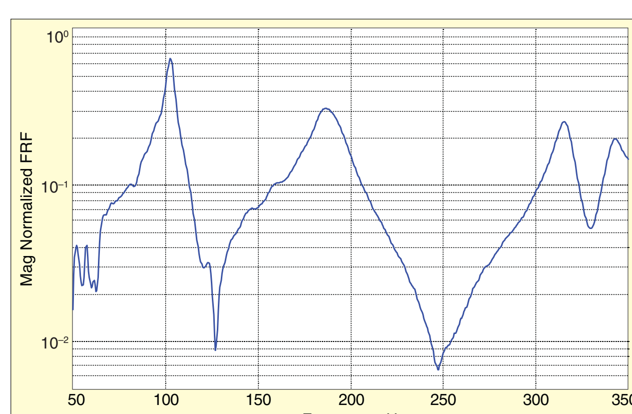

Figure 12. Typical FRF (instrument serial number 20060929144).

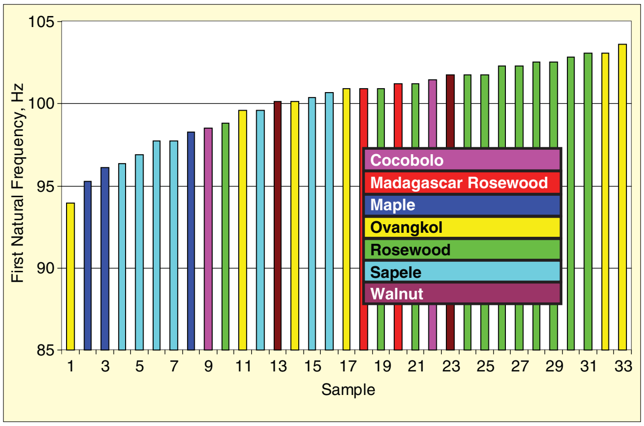

Figure 13. First natural frequencies of instruments in test pool.

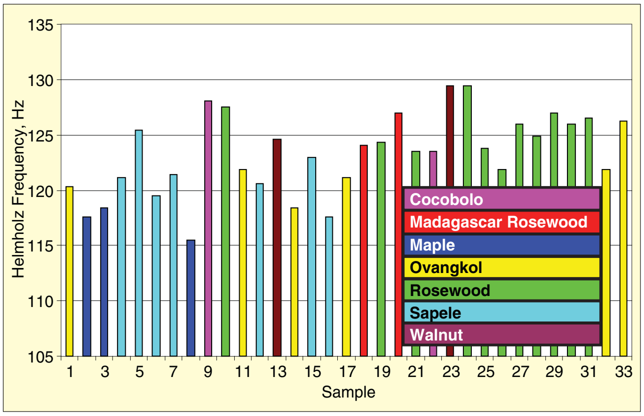

Figure 14. Helmholtz frequencies (rigid-body air mode) of test instruments.

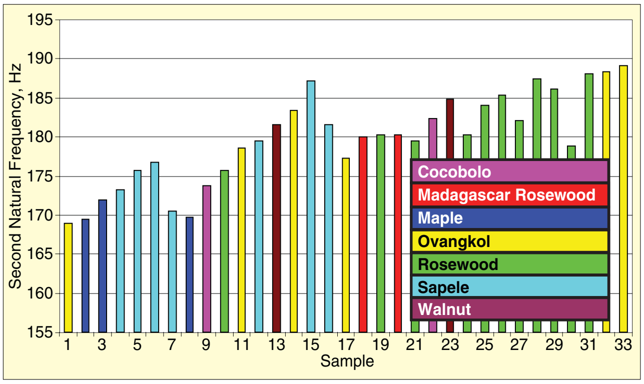

Figure 15. Second natural frequencies of instruments in test pool.

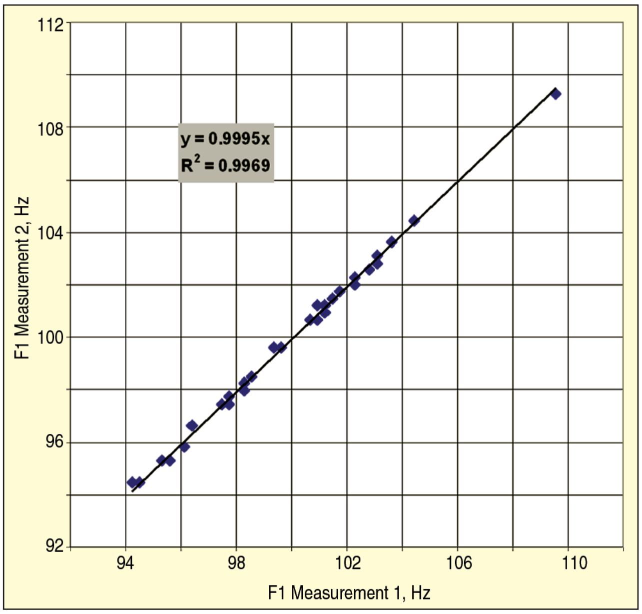

Figure 16. Isoplot from first natural frequencies.

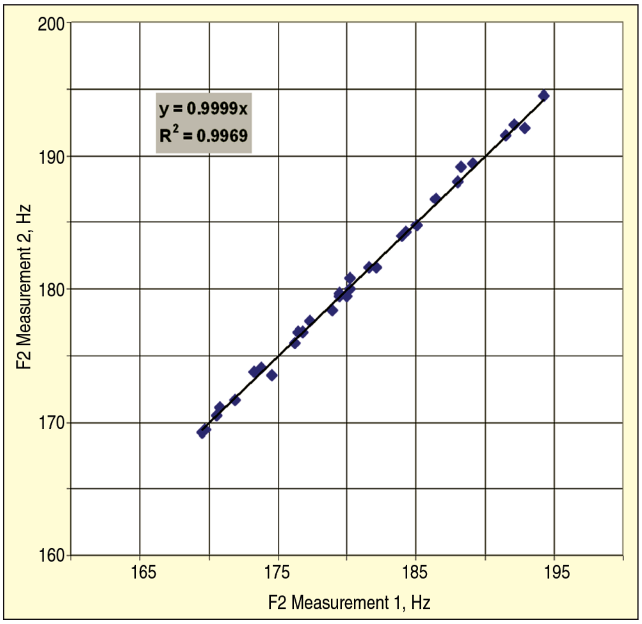

Figure 17. Isoplot from second natural frequencies.

possible that these models do not accurately capture the physics of the instruments; however, this option should be investigated only after there is clear evidence that the frequencies identified from the antiresonances are reliable. (We will cover more on this later.) The mean Helmholtz frequency was 123.4 Hz, and the standard deviation was 2.92% of the mean frequency.

Finally, Figure 15 shows the second resonant frequencies of the instruments, again sorted in the same order as the previous figures. Not surprisingly, the trend of increasing resonant frequencies from Figure 13 (first natural frequencies) is generally reproduced here. The second body mode typically shows little volume change, so the stiffness contribution of the enclosed air is small compared to the stiffness of the top and back. Therefore, the effect of variation in the structural properties of the instruments should be magnified. The mean frequency was 180.1 Hz, and the standard deviation was 3.11% of the mean frequency – higher than that for the first resonant frequency.

Test Method Verification

Since a relatively large pool of instruments was available, we ran two tests on many of them to establish statistically the validity of the method. This may seem like a needless addition to an article of this nature. However, we have seen numerous cases where the test methods were well established, and the repeatability of the data was "beyond question" only to find that no data existed to support the claim. In one case, the clearly established test method produced data statistically similar to a vector of random numbers.[13] Since the metric proposed here has not been used elsewhere, it is critical to establish at least once that the method is statistically defensible. A necessary condition is that the method produces repeatable results, as characterized on an isoplot.[3]

The isoplot method suggested by Shainin[3] is a simple tool to verify that the testing procedure can distinguish part variation from test variation. To construct an isoplot, the results of the second measurement are plotted against the results from the first. Distance between the points along the diagonal represents part variation. Distance perpendicular to the diagonal represents test variation. Thus, the ideal test would result in all data points along the diagonal. The general rule is that a box enclosing the data points should have an aspect ratio of 6 or more. If this is true, the test method is assumed to be capable of distinguishing test variation from part variation.

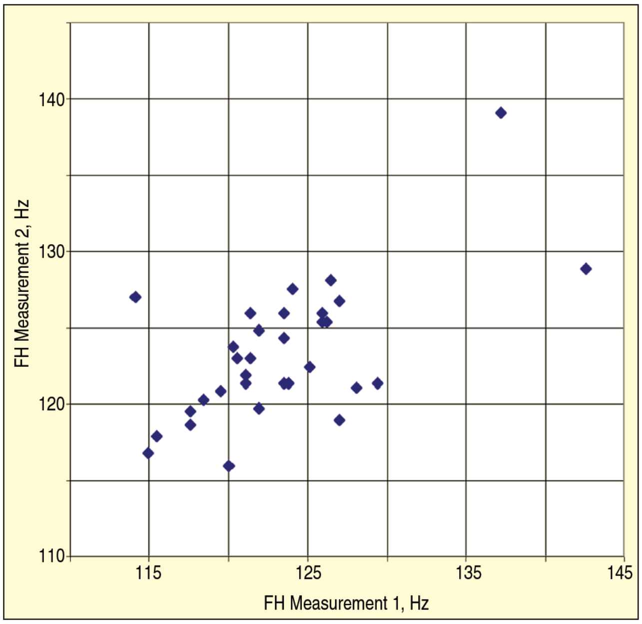

Figure 18. Isoplot from Helmholtz frequencies.

Figure 16 shows the isoplot constructed from the first natural frequencies. Clearly, the test variation is small compared to the part variation, adding confidence that the trends suggested by the first resonant frequencies are real and not an artifact of the test procedure.

Figure 17 shows that data from the second resonant frequencies also satisfy the requirements of the isoplot method. Thus, the part variation is much larger than the test variation, and trends suggested by this data can also be assumed to be real and not an artifact of the test procedure.

Finally, Figure 18 shows the isoplot made using the Helmholtz frequencies identified from the FRF plots. In contrast to the encouraging results from the first and second resonant frequencies, these data do not satisfy the requirements of the isoplot method; the test variation is not small compared to the part variation. This is not a complete surprise, since the signal-to-noise ratio at an antiresonance is, by definition, small. As is typical for this type of test, we often noted a significant decrease in coherence at antiresonance frequencies. So trends suggested by the Helmholtz frequency data should be evaluated carefully (perhaps with more testing) before being accepted as being real.

Our initial test setup used soft foam blocks to support the edges of the instrument and decouple it from the table. We found later that using felt blocks under the edges of the instrument markedly increased the coherence away from natural frequencies. We found that applying an exponential window to the response data also improved coherence at frequencies other than the natural frequencies. We used no windows on the input data for any of the tests.

Conclusions

The resonant frequencies of a guitar are a function of instrument geometry, mass and stiffness. These are, in turn, functions of the characteristics of the materials and the way they are processed to produce finished instruments. Variations in the resonant frequencies of completed instruments should be a good measure of the variation introduced by the production process.

With this in mind, we measured frequency response functions from a pool of acoustic guitars in the production facility of a large guitar manufacturer. We found that the standard deviation of the first natural frequencies was 2.23% of the mean frequency. The standard deviation of the second natural frequencies is 3.11% of the mean frequency. While there is some question about the quality of the Helmholtz frequencies measured from the test data, the standard deviation is low, 2.92% of the mean frequency.

We noted that the choice of side material appears to affect the first natural frequency. Rosewood generally results in higher fundamental frequencies, and Sapele results in lower fundamental frequencies. The results from instruments made using Ovangkol showed no clear trend, suggesting that more care should be taken in the selection process or that this species exhibits variation in mechanical properties that are not readily observable in the current grading process.

The low standard deviation values support the hypothesis that measuring resonant frequencies is a means of characterizing build variation. If the frequencies were unrelated to build variation, one would not expect the standard deviation to be low or that relationships between wood species and resonant frequency would be apparent.

The highly controlled nature of the build process used by this manufacturer would suggest that the standard deviations presented here represent a lower bound on the expected range of values. But this is only speculation until more data can be collected from other manufacturers.

Acknowledgement

We wish to thank Taylor Guitars for opening their factory. Dave Hosler and Brian Swerdfeger were generous in sharing their time and experience. Bob Taylor has set a standard for open access to knowledge that should inspire musical instrument makers everywhere.

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