FEATURE *by M. French and G. Bissinger*

TESTING OF ACOUSTIC STRINGED MUSICAL INSTRUMENTS—AN INTRODUCTION

Stringed musical instruments have been around almost since human society has existed. Archeologists speculate that the bow may have served as the first crude stringed musical instrument. Indeed, bows with crude sound chambers made from gourds or turtle shells are still being used by primitive peoples.[1] Trying to understand the empirical development of stringed instruments leads one into a field with a rich and interesting history that is well beyond the scope of this short article.

Nowadays the most common acoustic stringed instruments are in the violin family (which includes the viola, cello and the bass) and the guitar family. Other common stringed instruments include mandolins, dulcimers, banjos and pianos. For the purpose of this series, stringed instruments will not include pianos or harpsichords, which, while they certainly make music with vibrating strings, have complicated internal operation very different from the others, with such things as levers, hammers, damping mechanisms, etc. Luthiers—makers of stringed instruments—are generally assumed to be people who make instruments with a neck, body and a soundboard.

WHAT MAKES A GOOD INSTRUMENT?

This is definitely a contentious question—one might as well ponder the meaning of life. A good musical instrument is one that its player finds pleasing. Certainly, every player is different and different types of music require different characteristics in an instrument. Some basic requirements, however, are common to all instruments. The instrument should stay in tune, be comfortable to play, sustain notes well, be quick to respond, have a wide dynamic range, maintain a consistent sound across the pitch range, and have a pleasing sound for the player (and perhaps an audience). These requirements are, in large part, subjective. The requirement to stay in tune can be measured objectively by checking the natural frequencies of the strings and the "sustain" depends on the damping.

This article and those following in the series will concentrate on three specific acoustic instruments: the violin, the nylon string classical guitar and the steel string acoustic (folk) guitar. Solid body electric guitars are omitted because the sound is mostly dependent on the electronic processing and the dynamics of the instrument itself have largely secondary effects on the sound. While many other instruments could be included, the existing plucked/bowed string instrument literature primarily focuses on these three, and the mechanics involved are representative of a wide range of others. At the risk of encouraging stereotypes, desirable characteristics of these three instruments can be described in general terms.

Violins are used mostly for country, soft pop and classical music but in all cases their design and construction are heavily influenced by tradition.[2,3] While no two violins are exactly alike, the variation among instruments is surprisingly small, compared to violas and cellos. This high level of consistency has two interesting side effects. The first is that it is difficult for a casual observer to detect innovations in violin design (though an experienced musician or luthier would have no such problem). The second effect is that the number of potential variables when testing a violin is much smaller than for other instruments. Indeed, violin bodies are so similar that specific interior acoustic and structural modes have been given standard names that apply for almost all instruments.[4,5]

Classical guitars are, in a sense, halfway between violins and steel string acoustic guitars. They are played and tuned like most other guitars, but are firmly rooted in the culture of classical music and are, thus, almost as heavily influenced by tradition as are violins. Flamenco guitars even use the same wood tuning pegs as violins rather than the worm drive mechanical tuners used on almost all other guitars. There is slightly more variation in the design of classical guitars, especially in the interior strut configuration, and choice of woods, but most follow a very traditional design.[6] The most readily observable differences are often primarily aesthetic such as headstock design, inlays and rosette patterns.

Folk guitars, in contrast, are by far the most popular acoustic stringed instrument and seem to be about as popular as solid body electric guitars. While folk guitars share their origins with classical guitars, lutes and similar renaissance instruments, they have assumed the modern role of the popular instrument of the common man. Indeed, many skilled folk guitarists cannot read music. They have been built in a wide variety of shapes and sizes and using what seems like every possible material.[7] This variation offers exciting possibilities to luthiers and musicians, but greatly complicates the task of extrapolating specific test results to form general conclusions.

EXISTING WORK

The existing literature on the vibroacoustics of stringed instruments is far from extensive and far from authoritative when compared to that of more mainstream topics and forms only a very small subset of the literature on structural dynamics and acoustics. Indeed the published work seems to be either about the vibration or the radiation with few articles attempting to integrate both areas. There are some very good references and relatively complete work has been

Editor's note: *This series presents an overview of dynamic testing methods applied to stringed musical instruments. Articles in this series will present test methods applied to violins and guitars, analysis methods and examples of how experimental results have been used to improve the design and construction of stringed instruments. This first article is intended to provide the necessary background including a summary of existing work, the motivation for experimental investigations of musical instruments.*

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Fig. 1: Treble violin mounted in free-free, zero-mass loading modal analysis configuration (force hammer excitation, scanning laser response)

Fig. 2: A folk guitar undergoing vibrometer testing to determine string response

published in some specific areas (esp. see article collections edited by Hutchins[8,9]). Several good books have even been published on the general topic of the physics of musical instruments.[10–12]

For reasons discussed above, the most complete literature covers the violin. Hutchins[13] has arguably been the most influential worker in the field in the latter part of this century, publishing a substantial percentage of the literature herself, editing two collections of the major scientific violin literature, being one of the founding members of the Catgut Acoustical Society (formed specifically for the purpose of distributing archival quality research on acoustical stringed musical instruments), and acting as its permanent secretary for over thirty years.

Descriptions of acoustical and structural violin modes are reasonably standardized, but descriptions of sound quality are surprisingly un-standardized. One of the difficulties in qualitative evaluations is the lack of a standardized glossary of descriptive terms with clear definitions, although many terms such as bright, loud, muffled, harsh, balanced, etc. are commonly used by musicians.[14] Violin sound has only recently been modeled using normal mode structural analysis combined with boundary element calculations of the radiation.[15] This "vibration-radiation" model simplifies the sound production process by separating it into two basic elements:

- Strength of mode excitation—how strongly a *corpus* (violin sans neck-fingerboard, tailpiece, bridge) normal mode is excited at the bridge as determined by FRFs measured at the bridge feet (where most of the energy is transferred to the corpus).
- Radiation efficiency—how efficiently each normal mode radiates (mode shape and frequency dependent only) as computed with BEM software for each mode.

Violin normal mode excitation depends on the direction and location of the exciting force. Hammer-impact at a point on the bridge but from different directions generates significantly different sounds. When normal mode acoustic radiation is measured with a microphone array over a sphere and averaged, the strength of each mode is observed to be proportional to the strength of each normal mode's excitation;

when the radiation efficiency is factored in also the relative strengths of all mode radiations can be predicted quite well for both hammer directions.[16] These were the first successful predictions of violin "sound" based on a physical model. Advanced work is under way to model vibro-acoustic interactions.

Work on classical guitars is not as complete as that for violins. A number of references exist on modal response of guitar structures[17–22] and acoustic modes.[23] Descriptions of sound quality are relatively complete, though not so much as those for violins.

The state of folk guitars is the most uncertain of the three instruments. Certainly, much of the work describing material selection for guitars applies equally to classical and folk guitars, and the basic mechanics are well understood. In part because of the lack of standardization and in part because of the varied taste of buyers, general descriptions of sound quality are not available (and perhaps not even possible). For the same reasons, general structural models are still relatively simple.[24] A vibroacoustic model of a specific instrument would have to be developed with only limited reliance on previously published work and, in turn, might be of limited use for other instruments.

BASIC MECHANICS

In spite of the differences between the types of instruments, the basic sound producing mechanisms are quite similar. Kinetic energy from vibrating strings propagates through the structural connections to the body where the structure undergoes a forced response. The dynamics of the body is strongly conditioned by the presence of an enclosed volume of air and one or two ports to the outside. Typically the lowest strongly radiating mode is not a mechanical one. The lowest cavity mode A0, often considered a compliant wall version of the Helmholtz resonance, is the major sound source here. In the violin a significant recent development is the quite strong coupling observed between this mode and the next higher cavity mode.[25] This coupling changes the volume dependence significantly.

While all interior cavity air modes couple to the body, sometimes the coupling is so strong that it is no longer possible to even consider them cavity modes. In such cases a complete vibro-acoustic treatment is required. An interesting aspect of this coupling can be seen using interior gas exchange. By changing the molecular weight of the interior gas it is possible to vary the cavity mode frequencies while leaving the corpus modes essentially unaffected. When a cavity mode with a pressure profile similar in its nodal-antinodal surface pressure distribution to the velocity profile of a corpus mode coincide in frequency the coupling is maximized and the cavity mode effectively disappears.[26] Consequently the modal interaction via mass/stiffness interaction with the enclosed air must be considered a first order contributor to the dynamic (but not necessarily acoustic) response of the instrument. Since all the higher cavity modes of the violin have pressure nodes at the f-holes, little direct radiation is expected from these modes. It is not at all clear now how corpus motion induced by strong corpus-cavity mode coupling contributes to the overall sound of the instrument.

PROGRESS THROUGH DYNAMIC TESTING

The sound radiated by an instrument is produced by a strong interaction between the structure and the air both inside the body and the outside. Thus, a clear overall understanding of the structural dynamics of the instrument is a critical element in understanding how to produce a quality instrument. All good luthiers intuitively understand this, but the link between practicing luthiers and the modal test community is still a weak one, even though SEM sponsored a session at IMAC XIV to develop such interactions. So, much of musical instrument development proceeds in an empirical, Edison-like way, guided by individuals with keen ears experienced in their construction. Consequently, their research efforts do not have a clear guiding principle or focus. On the other hand the present omnibus CAD/CAE software, capable in concept of going from materials and shapes into the sound of a musical instrument, is friendly only to those able to speak its particular technical language very well. Moreover they must be willing to invest considerable time and money to be able to do so. Few makers or musical instrument designers can cope with the basic requirement of making a living/profit *and* of having the extensive time needed to start up and make such software aids truly operational.

Dynamic testing has been applied to musical instruments for about 30 years now. Indeed, there are few common tests methods that have not been used on stringed instruments. However, this test work has not broadly affected instrument design. In fact there is only one example extant where physical principles have been used to design bowed string instruments, the Hutchins-Schelleng Violin Octet.[27,28] This was not a "from scratch" endeavor, but relied on scaling mechanical properties of a "flat" violin to produce the octet. It is quite pertinent to note that the violin's "main air" (A0) and "main wood" resonances were scaled to fall at the pitches of the middle two strings of the instrument. However these were picked out from peaks in a loudness (acoustic) test; there was no mechanical normal mode characterization of the "main wood" resonance possible at the time.[29] For this reason alone the violin octet is of substantial interest to the modal analysis community.

There has been at least one noteworthy classical guitar design influenced by research results.[30,31] Still, a large number (probably the majority) of instruments are still designed by intuition and tradition. Most manufacturers have enough experience that evolutionary changes are low risk and likely to produce marketable instruments.

CONCLUSIONS

Musical instruments offer a fascinating subject for modal and acoustic testing. Even though the actual dynamics are quite complicated, the structures are very simple (so much so that excellent instruments are sometimes built in garages and on kitchen tables). Yet, we should never lose sight of the fact that the end of the trail for a musical instrument is how much it pleases the player and listener. Of course some industries nowadays consider this to be an important consideration too. One of the really wonderful things about the aforementioned dynamics investigations of musical instruments is that they have implications (and applications!) seemingly far from their complex, subtle, and entertaining source, offering insights into many other everyday dynamics problems.

There will be more articles in this series, describing the mechanics of stringed instruments in more detail, describing modal testing techniques, presenting methods for making sound field measurements, and providing specific cases in which the results of dynamic testing has affected instrument design.

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A Very Incomplete List of Web Resources

The Guild of American Luthiers	www.luth.org
VioLink	www.violink.com
The Association of Stringed Instrument Artisans	www.guitarmaker.org
The Catgut Acoustical Society	www.marymt.edu/~cas
The American Viola Society	www.viola.com
The American Musical Instrument Society	www.amis.org
Musical Instrument Maker's Forum	www.mimf.com (commercial site)
Frets.com	www.frets.com
Famous Guitarmaker Internet World HQ	www.cybozone.com/fg/index.html ■