FEATURE *Testing of Acoustic Stringed Musical Instruments: Part 2*
by M. French and G. Bissinger

MECHANICS OF STRINGED INSTRUMENTS

This is the second article in a series describing the testing of stringed instruments. The first article[1] provided an introduction to the topic along with an extended reference section for workers new to the field. This article presents a more detailed description of the mechanics of stringed instruments and suggested testing techniques. We will illustrate the mechanisms by which sound is produced and describe the experimental conditions that must be created in order to successfully test musical instruments. We also discuss the role of testing in the understanding and development of musical instruments. The next two articles in the series will deal with testing of violins and testing of guitars.

MECHANISM OF SOUND PRODUCTION

In principle, a stringed instrument is relatively simple. It consists of enough structure to hold a set of strings under a desired tension and an acoustic cavity with a flexible top and back to radiate sound when the strings vibrate. From this standpoint, the basic physics of most stringed instruments (barring the piano family) are similar.

A simple 3-DOF model has been propose[2] which models the instrument as a resonating cavity with two flexible surface as shown in Figure 1. While very simple, this model illustrates the basic implications of acoustic-structural coupling. (F(t) is the driving force, V is the volume, subscript references: h - cavity soundhole, t – top plate, b – back plate.)

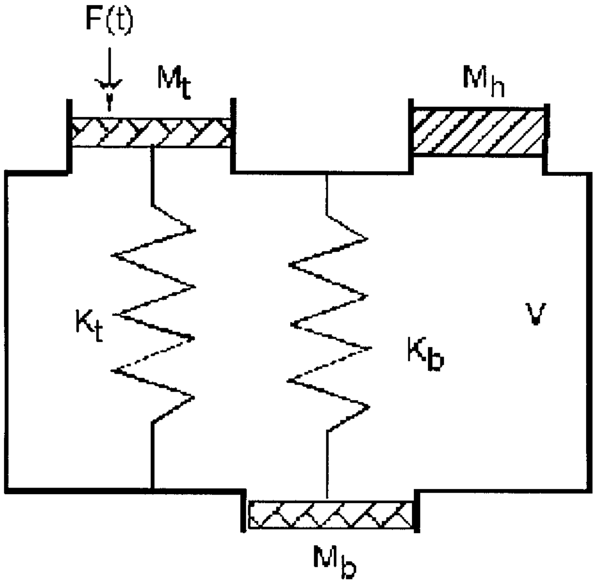

Figure 1 – 3-DOF Instrument Model

Typically, musical instrument testing involves measuring the pressure variation around or in the instrument and the motions of the instrument structure. Intuition and simple models such as that in Fig. 1 suggest that understanding the pressure variation and structural response is enough to characterize an instrument. Unfortunately the truth is that while this is certainly enough *mechanical* information to draw an equivalent electrical circuit there is nothing here about acoustic matters.

Subtle and not so subtle effects, such as the radiation efficiency of various normal modes, or how effectively the driving force is capable of exciting certain modes, substructure coupling especially to bending modes of the instrument neck, corpus-cavity coupling, mode dependent wall compliance effects and even cavity mode coupling are not incorporated in such models. Often these effects define the difference between superior and average instruments. Consideration of what is not measured is sometimes as important as what to measure, because it affects how tests are conducted and how results are used.

CHALLENGES IN MUSICAL INSTRUMENT TESTING

Testing musical instruments is not conceptually different than testing other structures. Interpretation of the results is, however, somewhat nontraditional in that the enclosed air cavity is an integral part of the system and cannot be ignored. Instruments – particularly violins - are typically very light and flexible and very sensitive to boundary conditions. Special care needs to be taken so that the instrumentation, excitation method, and support fixtures do not add mass or stiffness to the instrument.

Particularly refined instruments whose development has long since matured, e.g., violins, can undergo dramatic differences in sound quality with even small changes in the structure (such as a slight movement of the sound post or a small mass attached to the bridge). Thus, very light or non-contact sensors are often employed. Particularly good results have been achieved with laser doppler vibrometers and holographic or speckle interferometric systems.[3-5] For conventional modal testing, impact testing using a roving hammer is acceptable when expensive optical equipment is not available. Of course, care must be taken so that the impacts do not damage the instrument, a particularly serious problem with instruments using a soft wood like spruce on the top plate because of its elastic properties. For obvious reasons, roving hammer impact testing is not acceptable for particularly valuable instruments. The much better alternative is to use a fixed automated force hammer impacting an unfinished, easily replaceable substruture like the bridge on a violin and a scanning laser system.[6] One of us (GB) has had success in using CT scanners (normally used for medical imaging) to accu-

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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 resulte have been used to improve the design and construction of stringed instruments. This is the second article of the series.

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rately measure violin geometry and determine substructure densities. [7]

One continuing source of problems in modal testing is that of boundary conditions. When an instrument is being played, the conditions imposed by the musician's body are not known or easily modeled. It is, however, routine to assume that the restrictions imposed by the player are minimal and to test instruments in freely supported conditions. One of us (MF) has successfully tested guitars using soft foam supports. In that case, the lowest mode of interest was on the order of 65Hz and the effect of the low support stiffness was negligible. [8] However this support method can affect the measured damping significantly (~20%) even if mode frequencies are mostly unaffected. [9]

Another option in testing is whether the instrument should be strung or not. The strings are, by design, the most flexible parts of the instrument and, again by design, dominate the structural response. If the intent is to characterize the structure in isolation, the strings might be removed or heavily damped. On the other hand, if you wish to test the instrument in the form it will be played, string removal is not an option because they are an essential part of the structure and contribute in toto considerable stiffness to the assembled instrument.

Removing the strings of folk or classical guitars does not change the configuration of the instruments. However, archtop guitars and instruments of the violin family use string tension to hold the bridge and tailpiece in place. Thus, removing the strings greatly changes the basic configuration. Also in the violin the tailpiece is suspended at one end by the strings after they pass over the bridge and at the other with a heavy piece of gut or nylon passed over a small piece of hard wood and looped around the end button. It is a relatively freely moving substructure and some of its modes can couple quite strongly to corpus modes. In practice, damping the strings with a light piece of foam solves the problem if reliable damping measurements are not important. For example damping violin strings with foam adds approx. 20% to the measured damping. [9]

SIGNAL PROCESSING CONSIDERATIONS

Musical instrument testing imposes some unique requirements when processing signals from the various sensors. The ability to accurately estimate damping can be quite important, so high frequency resolution and relatively long sample times are often needed. The required maximum sample frequency differs greatly depending on whether structural or acoustic data is being collected. Acoustic data taken for the purpose of identifying coupled acoustic-structural modes should be sampled over the same frequency range as the structural data to aid in comparison. The acoustic data should be normalized to F(t) also, to create an acoustic FRF. Calibrated data permits later manipulation of the data to create a pressure/velocity ratio which is very informative about which modes radiate most strongly. However, data taken for the purpose of analyzing sound quality including qualitative evaluations should include frequencies up to the limits of human hearing (20 kHz). Direct acoustic recording with a DAT or CD unit would be recommended here.

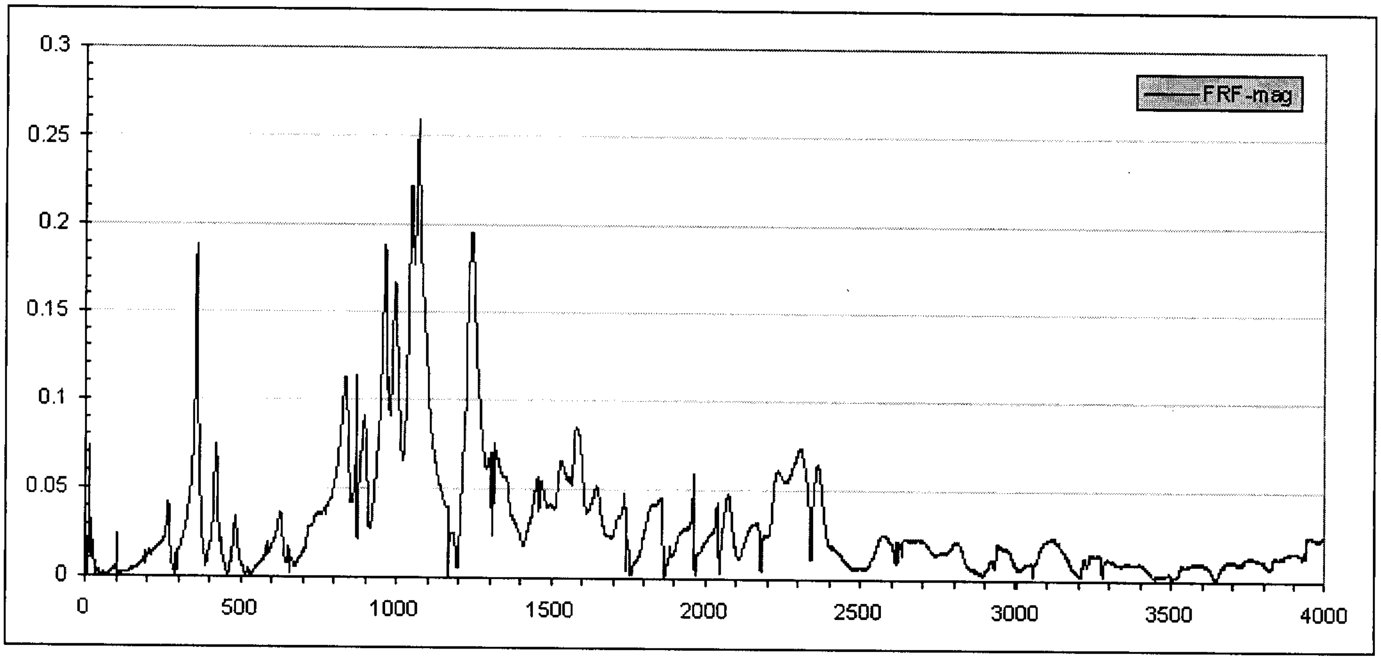

Fig. 2 — Typical mobility FRF (m/s/N) from a mezzo (a slightly larger variant of standard) violin over 0 – 4 kHz, measured in a minimal contact, low damping fixture with force hammer excitation at the bridge and a scanning laser vibrometer response measurement at one point on the top plate.

In stringed instruments, it is common that only the lower structural modes (including vibro-acoustic coupling) can be clearly identified. As frequency increases, modal density increases to the point that individual modes are not clear. In violins, most of the interesting individual modes occur below 1000 Hz. At frequencies above 3000 Hz, it becomes difficult to distinguish peaks in an FRF. Some of this can be seen in Fig. 2 from a very recent v/F mobility measurement by one of us (GB).

ROLE OF TESTING IN DEVELOPMENT OF MUSICAL INSTRUMENTS

Testing is sometimes done for instructional reasons or to understand basic response characteristics of a particular instrument. In other cases, it is done with the intent of refining a design or even for the purpose of making changes to a specific instrument. To date, much of the literature concentrates on characterizing specific instruments and trying to identify characteristics in the response that makes them particularly good or bad. There are some very interesting summary comparisons of large numbers of violins by Dünnwald [10] (using a single microphone and exciting violins electro-magnetically through a highly damped string) where properties of classes of violins, e.g., old Italian, modern makers, machine-figured, show some characteristic differences. Unfortunately no information about mechanical vibrations was collected hence no real knowledge about their normal modes exists.

The task of structural testing with the intention of improving a design is still poorly understood. Normal build variation can be as large as variations in design. Thus, correlating specific design features with the sound of a particularly good instrument is a very uncertain thing. As manufacturers have improved assembly techniques with numerically controlled equipment, better quality control, better material selection etc., build variation in some production instruments has decreased. Since most of these instruments are made of wood, even perfectly controlled sizes and shapes still carry no guarantee of achieving a desired sound. Perhaps a better, certainly more modern, approach is to look at the mechanical and acoustical *normal mode* characteristics of good instruments and try to reproduce these.

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