

Modal analysis as an acoustic tool in violin making

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Summary

Modal analysis is a fascinating acoustic tool for researching the individual vibration patterns of violins. By making the individual vibration behavior visible, the historical old masters become living sources of inspiration for today's violin making.

Modal analysis is one of the acoustic research tools used by Martin Schleske, the master violin maker. It makes it possible to capture the individual acoustic fingerprint of exceptional instruments.



Fig. 1: Modal analysis of a cello top in progress. The coordinate measuring table equipped with linear ball bearings and displacement transducers is used to determine the exact measuring points.

RESEARCH OF THE PRIMARY FUNCTION

This method originally comes from the aerospace industry. The first applications at that time were, for example, the vibration analysis of aircraft wings or satellites. While today the vibration behavior of the structure is only a subordinate function in many technical applications (e.g. in vehicle construction), the

situation is different with the violin: the interplay of all the vibrations determines the timbre, response, projection, dynamics – and therefore the primary function of the instrument.

IN WHAT STATE IS THE ANALYSIS CARRIED OUT?

In principle, the natural vibrations of the structure can be analyzed in any manufacturing state.

For the application of modal analysis, it does not matter whether the instrument is analyzed in a ready-to-play state (with strings strung) or in a working state (e.g. the free top, with and without bass bar).

In the case of restorations and new instruments, in the Martin Schleske Master Studio for Violinmaking often the vibrational behavior of individual production states is analyzed, as the free tops exhibit different natural vibrations than the finished instrument

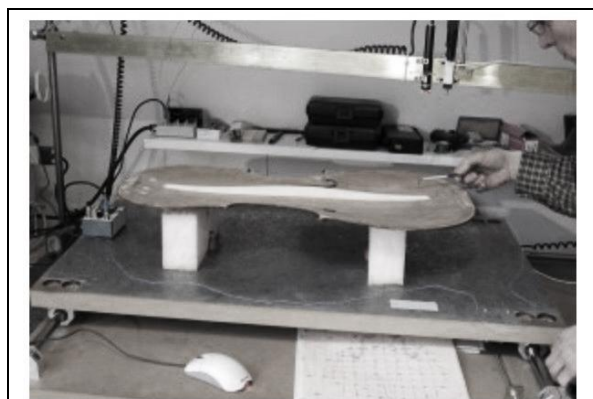


Fig. 2: Modal analysis of a cello top by Antonio Stradivari. Checking the new bass bellows.

Analyzing the natural vibrations of the white instrument is extremely helpful for estimating the sound of the future instrument based on the resonance profile (the so-called transfer function). For example, by analyzing the resulting natural frequencies during the finishing.



Fig. 3: View of the measuring station for modal analysis of string instruments in our workshop.

HOW DOES MODAL ANALYSIS WORK?

In the Martin Schleske Master Studio for Violinmaking, the instrument is excited at approx. 600 measuring points with the aid of a small impact hammer. The vibration response is recorded by a miniature accelerometer.



Fig. 4: Modal analysis of a violin by Antonio Stradivari from 1731

The signals from the impact hammer and the recording sensor are further processed using a so-called Fourier analyzer. A so-called transfer function is calculated for each measuring point.

An example of this is shown in the figure below. For the complete modal analysis of a violin, the transfer functions are measured at different coordinate points in all spatial directions.

The measuring points are determined using a coordinate measuring table mounted on linear shafts with ball bearings and transferred to the computer. If the instrument exhibits strong “dynamic mobility” at a certain frequency, even a small excitation force is sufficient to cause a large vibration response.

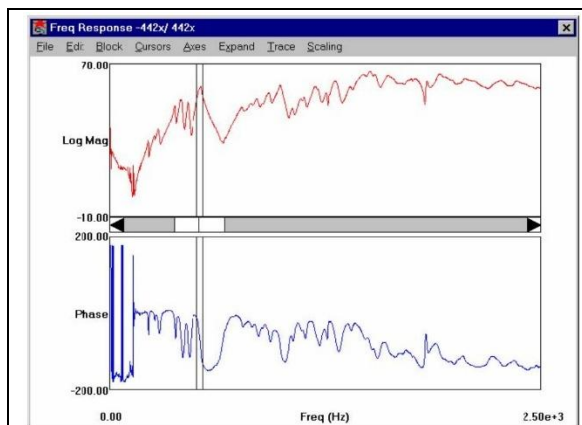


Fig. 5: Transfer function of a violin. The ratio of vibration response to exciting force is plotted as a function of frequency. Top: Vibration level (log. Mag.), bottom: phase.

The computer therefore calculates a correspondingly high value for the curve of the transfer function at this frequency. The resonances appear as local maximum values and become visible as “resonance peaks”.

The natural vibration modes of the instrument are then calculated from all the measured transfer functions. The user interface of the modal analysis program is shown below. Opened are windows for single measurements, definition of coordinates and grid lines, as well as wireframe model.

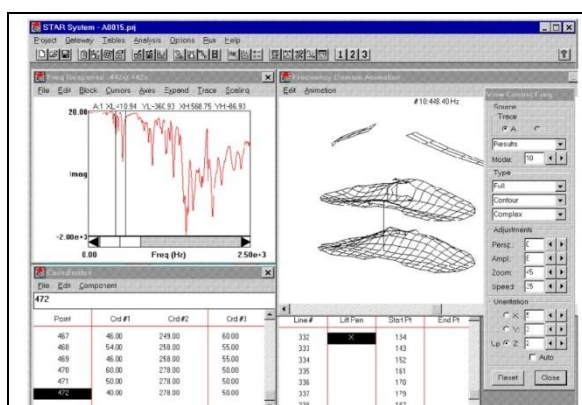


Fig. 6: Interface of the modal analysis program for evaluating the measurements, defining the geometry and calculating and displaying the vibration modes.

As a result of the geometry definition and the vibration measurements, the vibration modes are now visualized on the monitor using a wireframe animation in slow motion.

ACOUSTIC EXPERTISES

When creating acoustic expertises, the instrument is always examined in its ready-to-play state. The instrument does not necessarily have to be modified.

At the Martin Schleske Master Studio for Violin-making, modal analysis is used as a diagnostic tool to supplement intuition when adjusting the sound and building new stringed instruments.

RESULTS

A good violin has over 80 specific natural vibrations in its playing range. Each egg-gene mode is characterized by characteristic vibration bellies where it has maximum deflections and nodal lines where it remains at rest.

The results of the experimental modal analysis can be displayed either as “vibration maps” or as screen animations. By making the natural modes of vibration visible, modal analysis provides a basic understanding of the instrument's resonances. This not only makes the sound of the instrument audible, but also makes its cause visible. In this way, an intuitive feeling for the steps in the development of the instrument that determine its sound grows – such as the shaping of the arching, the finishing or the design of the bass bar.

The vibration movements are not a numerical simulation, but the measured vibration behavior of the actual instrument. The amplitudes are greatly magnified and the vibration frequency is greatly elongated.

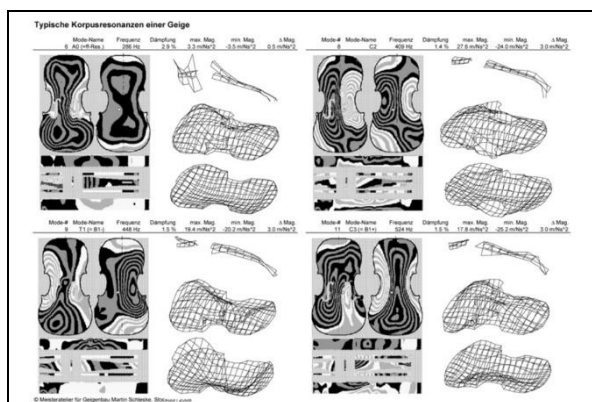


Fig. 7: The typical natural modes of the corpus resonances. Measurement by means of experimental modal analysis (595 transfer functions). Representation by “vibration maps”: Interpolation and contour plot with lines equal to amplitudes (contour lines). View of the plates from the outside. Phase convention: Simultaneously expanding (black-grey) and simultaneously compressing (white-grey) corpus areas are considered to be in phase. Nodal lines corresponding between black and white height line. Top on the left, back on the right, sides of the bass bar side below, side views and top view of tailpiece and fingerboard, sides of the soundpost side. Wireframe and animation: tailpiece and fingerboard (top), top (center), back (bottom). Zero position and maximum deflection. Instrument: Antonio Stradivari 1712 “Schreiber”.

The dynamic animations show the natural vibrations of a violin using the example of an instrument by Antonio Stradivari from 1712. An impressively high mode density of over 65 resonances in the frequency range up to 2000 Hz can be seen. Four of the typical corpus resonances of this instrument are shown in fig. 7 as “vibration maps” (left) and as wire grids at maximum deflection superimposed on the rest position (right).

INDIVIDUAL ACOUSTIC CHARACTERISTICS OF A MASTER OR A SCHOOL

Our modal analyses of various violins by Antonio Stradivari show that there is a clear correspondence in the formation of essential body resonances.

Frequency intervals and couplings between the modes are strikingly similar. In contrast, the frequency interval between the two main corpus resonances (T1 and B1) in Guarneri del Gesù is considerably larger. Knowledge of such and similar acoustic characteristics of different masters or schools is a helpful addition to the traditional, purely stylistic and constructive description of string instruments.

Knowledge of the acoustic characteristics typical of a master is an essential guideline for targeted tonal work in the construction of high-quality stringed instruments.

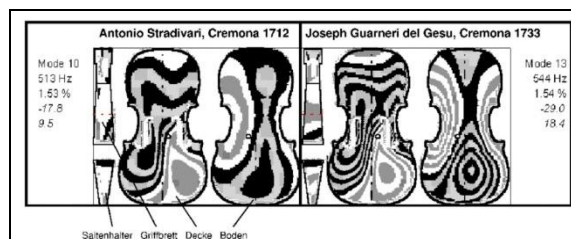


Fig. 8: B1 main body model. Measurement of a violin by Antonio Stradivari (left) and a Guarneri del Gesù (right). The diagram shows the eigenmode (residual) of the B1 main body mode calculated from the measured transfer functions (v/F). Measurement in ready-to-play condition with damped strings. View of both plates from the outside.

INTERPRETATION

The vibrational shape of the B1 mode is relatively similar on both violins. However, the Guarneri del Gesù exhibits stronger body amplitudes, whereas the B1 mode of the Stradivarius is coupled with a fingerboard torsion, which is why the B1 mode is split into two effectively radiating modes (at 512 and 523 Hz).

The damping of the B1 mode is very similar for both violins (Stradivari 1.53%; Guarneri 1.54%). This is a helpful control measure for the acoustic effect of the violin varnish used.

The natural frequency of this vibration mode of the two violins is relatively different at 512 Hz (Stradivarius) and 544 Hz (Guarneri des Gesu). This natural frequency is an effective guideline for the timbre of the instrument, as the B1 mode can be regarded as a kind of “modal barometer” for the construction of the instrument.

Technical details of the illustrations: Line spacing = $5(\text{Hz} \cdot \text{m}) / (\text{s} \cdot N)$. The line spacing is defined as the distance between two adjacent contour lines of the same type (the amplitudes are therefore shown in absolute values.) Phase convention: Expanding or compressing plate areas of the corpus are considered to be of the same phase and are shown accordingly with a grid of the same type (i.e. gray-white or gray-black).

Designation next to the eigenmodes: Mode-#; frequency (Hz); attenuation (%); max. neg. residue mag; max. pos. residue mag. $(\text{Hz} \cdot \text{m}) / (\text{s} \cdot N)$.

FAULT DIAGNOSIS ON EXISTING PROBLEM INSTRUMENTS

By measuring a large number of different instruments, our laboratory has created a comprehensive database of the typical acoustic and constructional properties of violins, violas and cellos.

Modal analysis of problem instruments is an effective diagnostic tool based on knowledge of the vibration characteristics that are typical of good instruments. By revealing modal anomalies (e.g. in the distribution of the vibration amplitudes of characteristic

modes), conclusions can be drawn about design or setting-related defects (soundpost, bridge, etc.).

SUMMARY

The beauty of modal analysis lies in the fact that it makes it possible to look over the shoulders of the great old masters. The old Italian models such as Stradivari, Montagnana, Guadagnini or Guarneri thus become inspiring teachers in our daily workshop work.

The acoustic fingerprint of these great masters reveals a genius that is a lasting incentive and an incontestable test of our own work and learning. Nevertheless, I am not subservient to them. Even though it was appealing in my early years to make sound copies of famous instruments with the help of acoustic tools and to research the resonance profiles of the great masters in detail, over the years I have developed my own artistic and tonal signature.

FOR MORE IN-DEPTH STUDY

Schleske, Martin: Eigenmoden der Schwingung im Arbeitsprozess einer Geige. CAS Journal Vol.3, No.1, (Serie II), Mai 1996.

Schleske, Martin: Empirische Werkzeuge im zeitgenössischen Geigenbau: Teil I. Analyse von Design, Materialien, Lack und Normalmodi. CAS Journal Vol. 4, No.5 (Serie II), Mai 2000.