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ON DEVIATING RESULTS OF OPTICAL HOLOGRAM INTERFEROMETRY AND MODAL ANALYSIS OF A VIOLIN

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Abstract

Two prominent normal modes of a violin at 380 Hz and 460 Hz are presented and discussed. Deviations are found between the modal shapes measured holographically and those obtained by modal analysis with digital equipment. The deviations imply that great caution is motivated in interpreting normal modes of objects with complicated structures, boundaries and material. The real-time observations with the optical modal analysis offer hereby advantages.

INTRODUCTION

The vibrations of a complex and linear dynamic system are often described as a weighted sum of its normal modes. Therefore, normal modes, i.e., the resonances, are fundamental properties to seek, when one wants to specify the properties of the dynamic system such as the violin body. The eigenfrequencies of the normal modes, i.e., the resonance frequencies, are in general simple to record, but the distributions of vibration amplitudes are difficult. The violin is made of wood (anisotropic), has complex boundaries and complicated design of its parts. Its normal modes of vibration cannot be predicted by simple means.

Optical methods to record vibration modes were introduced about twenty-five years ago (Powell & Stetson, 1965; Stetson & Powell, 1965; Vest, 1979). These methods have been used to investigate normal modes of violins, lately transient phenomena too (Alonso Moral & Jansson, 1982; Jansson, 1973; Jansson, Molin, & Sundin, 1970; Molin & Jansson, 1989; Molin, Lindgren, & Jansson, 1988). More recently, digital electronic equipments (hardware and software) have been developed for modal analysis (Bendal & Fiersol, 1980; Ewins, 1986). It is in common use in the engineering community and has also been used to investigate violins (Jansson, Bork, & Meyer, 1986; Marshall, 1985; 1987). The optical and the digital methods have partly given the same results and partly different results for violins. It is therefore interesting to verify the dissimilar results and to try to understand them. An investigation of a simple object, a metal plate, with the two methods gave consistent results but implied different advantageous areas for the optical and the digital modal analysis, respectively (Kyösti, Ek, & Molin, 1985). The present work reports from measurements on a violin with both methods sketched.

OPTICAL MODAL ANALYSIS

If a dynamic system is excited at a single frequency, its vibrations consist of a weighted sum of its normal modes. When the excitation frequency is adjusted close to the eigenfrequency of a normal mode, the other normal modes tend to be "short-circuited" and to be of minor importance. Thereby, the normal mode of the nearby eigenfrequency is enhanced. Furthermore, if the supports of the system are shifted to nodal lines of the investigated normal mode, but away from nodal lines of disturbing modes, the vibrations of the investigated normal mode are

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The investigated mode can be still more favoured by selecting an excitation position close to an antinode for the investigated mode but at nodes for disturbing modes. If not sufficient, more than one excitation point may be used.

The optical modal analysis is conducted in two steps with two optical systems using the knowledge presented above. In the first step, the normal modes are sought, localized, and brought out by means of a real-time technique. In the second step, permanent records are made of the identified normal mode vibrations.

The normal modes are sought in the following way. An excitation point and a suitable number of supporting points (often three) are selected. The excitation frequency is slowly swept through the range of interest and the resulting vibrations are watched by the real-time technique. The frequencies of large vibrations are noted and revisited for detailed investigations. Thereby, the excitation is adjusted to be efficient, usually in a single point. The supports are shifted to lines of no motion. The vibration amplitudes, and especially the positions of maximum and the positions of no motion, are watched while the frequency is slowly altered.

The criteria used to decide whether the watched vibrations at a specific frequency represent a normal mode or not, are the following. A maximum antinode amplitude should be obtained at a specific frequency. The positions of no motion and maximum motion should neither shift for a moderate frequency shift around the "suspected" resonance frequency nor for a moderate change of the excitation amplitude at that frequency. If so, the observed vibrations are considered to represent a normal mode with the no motion lines being nodal lines, the positions of maximum amplitude being antinodes, and the specific frequency being the resonance frequency. The whole procedure is repeated for each "suspected" normal mode. Finally, permanent records are made with optimized excitation point (or points), supporting points, and an excitation amplitude to give a picture as informative as possible.

The relative phases of vibrations can be measured by using a vibrating reference mirror in the interferometer but often the vibrations can be interpreted without this information.

In the interferometer, a laser is used as light source (Vest, 1979). A vibrating object surface gives a varying optical path length in one of the interferometer beams which results in interference fringes representing isoamplitude lines of vibration (cf., Figs. 2a and 3a). The increase of vibration amplitude between neighbouring isoamplitude lines depends on the wavelength of the laser light, the angle of illumination, and the angle of observation. Maximum sensitivity for vibrations perpendicular to the surface plane is obtained with the illumination and observation also perpendicular to the surface.

The vibration resolution of the optical technique is approximately 0.1 μm. The presentation of the vibrations in form of isoamplitude lines is well adopted for visual and digital analysis.

The real-time interferometer used, the VibraVision, works at TV frame-rate (25 Hz) and is thus updated with 25 interferograms per second (Ek, Molin, & Biederman, 1985). The method employs in reality time-average technique with the isoamplitude lines spaced at maxima of a zero-order bessel function of the vibration amplitude, and the nodal lines are clearly shown as the whitest and broadest fringe. The stability of a recorded modal pattern is easily tested by shifting supports, excitation position, and frequency. The real-time interferometer is not larger than a suitcase and can easily be moved into a workshop.

For the permanent records, double pulsed hologram interferometry with a ruby laser as light source was used. The white and dark fringes fall at maxima and minima of a cosine function (cf., Figs. 2a and 3a), i.e., the vibration steps between the fringes are constant with no enhancement of the nodal lines. The resolution of the relative vibration amplitudes is limited by the number of fringes that can be observed. The short exposure time (about 25 ns) of the ruby laser makes vibration isolation of the setup unnecessary.
DIGITAL MODAL ANALYSIS
Modal analysis of linear systems with digital equipment is a common method today to record normal modes of vibration (Jansson & al., 1986; Marshall, 1985; 1987). Usually an impulse hammer is used to excite, in succession, a large number of points and for each excitation point, a time sequence is recorded at one (or several) reference point(s). By recalculating each such impulse response into a frequency response by means of a computer, a measure is obtained of the vibrations for all frequencies simultaneously at each point. From the frequency responses, normal modes of the system are calculated by the computer.

The sketched digital method sets small demands on the stability. The holding structure should, however, not be allowed to influence the measurements. This condition can be met by hanging the object, the violin, in thin rubber bands. The method covers a wide frequency range. The limits are mainly set by the noise of the signals.

In the calculation of frequency responses and modal shapes an assumption about the material properties is done, most often to be a linear relationship with no damping and with the normal modes of vibration being well separated in frequency. These assumptions are difficult to fulfil in advance and care has to be taken to check these assumptions.

This common method of digital modal analysis is, however, not a real-time method. Therefore, it is difficult to optimize measurements and to test the stability of recorded mode patterns. Furthermore, it is a point method and the number of exciting and measuring points limits the spatial resolution.

EXPERIMENTS AND RESULTS
The optical arrangements, as sketched in Fig. 1, were used. The real-time interferometer and the double pulsed laser for the permanent records were placed on a table. On another table, the optical system for studying the violin front and back sides was placed.

Fig. 1. Optical setup: H - hologram film holder (camera back), M - mirror, O - object of investigation (violin), L - negative lens diverging the light beam, RUBY - $I\ J$ double pulsed ruby laser, HeNe - continuous He-Ne laser for optical adjustments, and VV - VibraVision the real-time interferometer. Lines with arrows mark optical paths. The length of the large table is 2.5 m.
The violin was set into vibration by means of a small magnet (0.3 g) attached with wax to the violin surface and an electrical coil fixed in an armature, vibration isolated from the violin. A sinusoidal current through the coil gave a vibration-force amplitude at that frequency over a small airgap. The excitation frequency was slowly altered and the vibration modes were studied with the real-time interferometer.

For the present investigation of the reference violin HS71, two especially interesting vibration modes at 380 Hz and 460 Hz were investigated. The lower mode is a prominent vibration mode of the whole violin body. The higher mode is the main sound radiation mode at low frequencies. The 380 Hz mode came out with little problems in determining excitation and supporting positions. The mode showed clear nodal antinodes and nodal lines, mostly twisting along the length axis of the violin. It had six antinodes along the edges, two mainly horizontal nodal lines and one central vertical nodal line (cf., Fig. 2a).

It was more difficult to obtain a simple and clear picture of the distribution of vibration amplitudes of the 460 Hz mode. A prominent and stable vibration maximum was found at the left f-hole reminding of the fundamental plate mode, cf., earlier measurements (Alonso Moral & Jansson, 1982; Jansson, 1973; Jansson & al., 1970; Molin & al., 1988). At the right f-hole a minor maximum was found and between the two maxima a no motion line (cf., Fig. 3a). The vibration amplitudes were small along the edges and in the back. The normal mode was interpreted to consist mainly of an antinode at the left f-hole and with no clear nodal lines (except at the right f-hole), but possibly along the edge of the violin, i.e., close to a top plate mode.

Permanent records were made with the double pulsed laser interferometer. The two vibration recordings, see Figs. 2a and 3a, show simultaneously the violin top side and via the large mirror the back side. The black lines mark the isoamplitude lines (because of differences in illumination and observation directions for the front and back sides, the isoamplitude lines of the back side correspond to approximately 1.7 times larger amplitude than those of the front). The bar seen at the lower left in Figs. 2a and 3a is the excitation coil armature; its top marks the excitation position. The excitation positions were chosen to separate the two modes found in the real-time survey as far as possible.

In the double-pulsed recordings, the nodal lines cannot be distinguished from any other white fringe but are easily determined in the real-time measurements. They coincide with the white zero-order fringe and are sketched in Fig. 2c. The antinodes (six at the edges) are found at the positions of maximum amplitude by counting the number of black and white lines (fringes). The positions and relative amplitudes of the antinodes are also sketched in Fig. 2c. In the recording, the excitation point is close to the antinode of the 380 Hz mode but at a position of low vibration amplitude for the 460 Hz mode. Two semi-soft supports (erasers of rubber) were placed close to the center line at the bottom edge and one at the upper edge, i.e., close to the vertical nodal line.

The 460 Hz mode is shown in Figs. 3a and 3c in a similar way. The supports were placed at the edges and at the nodal lines previously found in the digital modal analysis (to avoid suppression of the digitally recorded mode shape), see Jansson, et al., (1986). The excitation point was selected close to a nodal line of the 380 Hz mode.

Previously, during a two months' stay of one of the authors as "Gastwissenschaftler" at the Musical Acoustics Laboratory of the Physikalisch-Technische Bundesanstalt in Braunschweig (Western Germany), modal analysis via the impulse response was made of four violins including the reference violin HS71 (Jansson & al., 1986). In these experiments, it was found that the single degree of freedom method (SDOF) was sufficient for the analysis. The modes obtained at 380 Hz and 460 Hz are shown in Figs. 2b and 3b. The directions and magnitudes of vibrations are marked with bars, one bar for each excitation point. Antinodal positions, amplitudes, and nodal lines are plotted in Figs. 2d and 3d.
Fig. 2. The 380 Hz mode a) optical (double pulsed) interferograms showing the isoamplitude lines, b) digital (modal analysis) result with bars showing vibration amplitudes, c) antinodes and nodal positions extracted from the optical measurements, and d) antinodes and nodal positions extracted from digital results. Both plates in c and d are shown as seen from the top plate side, full thick lines mark reliable nodal lines and broken thick lines mark plausible nodal lines, plus and minus signs mark phases of vibration, and numbers relative vibration amplitudes at antinodes.
DISCUSSION

For the 380 Hz mode, the optical and the digital modal analyses give closely the same results, see Figs. 2c and 2d. The positions of the nodal lines and antinodal areas show at least a fair agreement and the relative antinodal amplitudes at least a qualitative agreement. Both analyses show that the top and back plate vibrate in phase, i.e., a vibration mode of the complete violin body. This normal mode was also found in previous investigations, both with optical and digital modal analysis, thus indicating a general validity of the result (Alonso Moral & Jansson, 1982; Jansson & al., 1986; Marshall, 1985).

For the 460 Hz mode, the position of the major antinode at the left f-hole and a vertical nodal line at the right f-hole (on top of the sound post) are found with both methods. The digital analysis shows in addition two mainly vertical nodal lines for the front (the top) plate, two mainly transversal nodal lines for the back plate, and vibration maxima at the waist of the back. The transversal nodal lines of the back plate are not found in the optical measurements in spite of favourable excitation and supporting positions in the optical modal analysis. The vibration maxima at the waist found in the digital analysis have so large amplitudes that they could not possibly be "masked by noise", if present in the optical analysis.

The optical analysis of the 460 Hz mode implies that the vibrations are mainly in the front plate (the top plate) with a rigid support of the sound post, and with only little "spilling over" the edges to the back plate. The digital analysis implies that the front and back plate vibrations are approximately of equal amplitude; maximum vibration in the front plate but vibrations of the same magnitude at the waist of the back plates.

The deviating results of the optical and digital analysis are typical for the 460 Hz mode (Alonso Moral & Jansson, 1982; Jansson, 1973; Jansson & al., 1986; Marshall, 1985). In digital modal analysis of a second violin, Marshall (1987) describes the mode corresponding to our 460 Hz mode as "bending and breathing of corpus." In the optical analysis, we are studying the real vibrations directly with no calculation algorithms or material assumptions involved, and we believe that by monitoring in real-time, we have obtained the "correct" description of the 460 Hz mode as a "breathing mode" (only small tendencies to bending in the back).

Thus, we reach the following conclusions. The optical modal analysis with information from every point on the object surface and without any mass-loading sensors gives the modal shapes with higher accuracy. As the vibrations can be observed in real time and the measurement situation can be optimized, the optical modal analysis is the best choice for the modal analysis of complex vibratory systems from small to moderate sizes and with visible vibration parts such as the violin. Furthermore, the effects of changes in support and excitation of the investigated object can be visualized directly. Digital modal analysis with impulse excitation is well adapted to engineering measurements of normal modes in the workshop and can be used on objects from moderate to large sizes also with nonvisible parts and very small vibration amplitudes. The digitally stored data are furthermore ready for calculations and numerical experiments with commercially available modal analysis programs. The used digital method is, however, not so well adapted to measure mode shapes with high accuracy, especially not on complicated nonlinear objects. Erroneous results may be introduced.

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Fig. 3. The 460 Hz mode results displayed as in Fig. 2.
References: