THE INFLUENCE OF VARNISH ON THE PROPERTIES OF SPRUCE PLATES

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1. INTRODUCTION

There has been considerable discussion over the years of the possible influence of varnish on the sound and playing properties of musical instruments. A certain amount of information is available, suggesting effects which are small although quite possibly significant [1]. Where such data has been obtained from varnished wood samples coming close to actual instrument-making practice, it has almost invariably been deduced from resonance tests on varnished strips, cut along and across the grain. As has been pointed out, one cannot measure all the relevant elastic and damping parameters from strip tests [2]. Even for the simplest case of the influence of varnish on flat plates of quarter-cut wood, further measurements are necessary for a complete description at even the first level of approximation.

It has been shown that measurements of resonant frequencies of low-frequency modes of free-edged rectangular plates provide one quite efficient way to determine a more complete set of data [3]. Accordingly, a first attempt has been made to apply this approach to plates of spruce with various varnish finishes applied to them. Attempts have been made to measure other physical parameters of the same set of samples, such as surface hardness. This paper describes the experiment, some preliminary results obtained so far, and some lessons learnt about pitfalls to try to avoid in future experiments of a similar nature.

2. SAMPLES AND EXPERIMENTAL TECHNIQUES

The starting point was a plank of quarter-cut spruce, well air-dried, of the kind used in soundboards of keyboard instruments (kindly supplied by David Rubio). This had very well aligned annual rings running the length of the plank with very little visible variation in pattern from one end to the other. By cutting this plank into a series of small square plates (132×132mm), we sought to achieve the closest we could to a set of identical specimens of wood. The plank was thicknessed by plane, not scraper, to the best approximation which could be achieved to a uniform thickness of 2.0mm. Scraping was avoided since a previous study [4] has highlighted how much compaction of surface layers can be caused by scraping, leaving a surface unlikely to be stable since humidity cycling will lead to some degree of recovery of the original form.

In all, seven plates were produced. These were then treated with a variety of finishes, one being left untreated as a control. The three most interesting finishes were those on samples 3, 5 and 6, which were three different complete violin-varnishing treatments, each being applied in parallel with the varnishing of an actual instrument. These finishes were: no. 3, synthetic pozzolanic ground layer, rosin oil, and oil varnish containing pigment in glaze layers; no. 5, traditional spirit-based gum varnish; and no. 6, particulate ground, rosin oil, and brushed-on coloured oil varnish (a commercial terpene resin violin varnish). For comparison, sample 7 was varnished with three coats of a modern synthetic varnish (Manders interior eggshell varnish, clear).

No attempt has been made to keep the samples in temperature and humidity controlled environments. Instead, they have all been kept close together in an office subject to the usual range of climatic and winter heating variations. They are stood in such a way that air can circulate around them, and every few months a series of measurements is made of weights, resonant frequencies and damping factors. The measurements are carried out in the same room in which the samples are stored, so that they are in equilibrium with that environment before measurements commence. This avoids the problem encountered previously of samples being taken to a laboratory for measurements, and changing significantly during the hour or two that a complete test takes as they acclimatised to the new surroundings. It was hoped that useful information would be collected about the extent of variation of the various material parameters under the range of climatic conditions to which musical instruments in the UK are ordinarily exposed.

The tests which have been carried out were all quite standard. Resonant frequencies and damping factors were measured in the manner described previously [3]. Thicknesses at several points in each sample were measured by micrometer, and the samples were weighed. Indents were made with a micro-hardness tester, including some in small test samples cut from the main specimens which were mounted and gold-coated so that they could be examined in the scanning electron microscope. This allowed thicknesses and fracture characteristics to be studied.

3. PRELIMINARY RESULTS AND SNAGS

It is intrinisic to a test like this that full results will only emerge after some time, when the measurements have been repeated many times under different conditions. However, some preliminary results are available, and these have revealed some snags which in retrospect are quite obvious. Changes are being made to the details of the experiment in an attempt to limit the effects of these snags.

The first snag concerns the growth pattern in the plank of wood selected. Although the annual rings were straight and uniform along the length of the plank so that the separate plates are quite closely similar, the growth pattern in the transverse direction leaves something to be desired. At a point approximately one third of the way across each plate, the average spacing of rings suddenly doubles. This presumably results from felling of neighbouring trees, improving growth conditions for the one used here. Its effect on vibration behaviour is to impose a small but significant variation in elastic properties across the width of the plates, which causes distortion of the mode shapes. This effect is most significant for the mode which one would describe as the "lowest long-grain bending mode". Instead of showing two approximately straight node lines running parallel to the annual rings, this mode has considerably distorted node lines. While its frequency can still be used to estimate the corresponding elastic constant, one would expect its damping factor to be significantly reduced by mixing other, more highly-damped motion with the pure long-grain bending so that a good measurement of long-grain damping is not obtained.

The second snag is that if a thin wooden plate is varnished on one side only, it shows a marked tendency to warp in the cross-grain direction. A compromise must be struck here if measurements of all relevant parameters are to made at all. We deliberately chose rather thin plates (2.0mm), knowing that we would be looking for rather small effects from the varnish layers. Thinner plates increase the influence of varnish relative to wood, making measurements of the small changes more accurate. However, thinner plates are obviously more prone to warping. The effect of cross-grain warping is to produce significant long-grain stiffening (the "corrugated iron" effect). This again limits the accuracy of predictions based on the long-grain bending modes.

A partial answer to both snags is to cut the plates into smaller pieces. By cutting along the line of the change in growth pattern, the magnitude of the influence of the growth change can be studied by measuring each side separately. The disadvantage is that smaller plates are harder to support in such a way that frequencies and damping factors are not perturbed by boundary effects. Results are not yet available from the smaller samples, but they will form the next stage of work on this project.

For now, we report some of the conclusions from the tests on the original plates. First, we discuss the results of weighing and microscopical examination. The apparent mean thicknesses of the three "violin varnish" coatings all proved to be remarkably similar, at around 60–70μm. The synthetic varnish was thinner, at 30μm. The added masses of the different varnishes told a rather different story, suggesting perhaps that some had penetrated the wood more significantly than others. The mass per unit area was around 0.035kg/m^2 for the synthetic varnish and the spirit varnish, but the two oil varnishes were heavier, in the range 0.065–0.075kg/m^2. For the particular thickness of samples used here, the effect of varying humidity on the mass of the underlying wood was roughly comparable with the added mass of the various varnishes. The weight of any given sample is observed to vary over a range of about 1.4%. All samples are untreated on at least one side, so all absorb and lose moisture more or less equally well, and the relative weights remain quite accurately the same.

The attempt to measure (Vickers) hardness was less clear-cut. The typical indent size with the smallest load on our micro-hardness tester was around 70μm across, and correspondingly about 10μm deep. This is not sufficiently smaller than the varnish thicknesses for the method to produce accurate results — the manufacturer specifies about 100μm as the thinnest layer compatible with these figures. However, when combined with examination of the indents in the SEM, some interesting observations could be made. On the bare wood, the hardness varied very greatly, from around 20 on late wood to values in the range 1–5 on early wood. The spirit varnish had a hardness around 7, and was obviously brittle. The indenter had caused cracks to form, and the fracture surface at a split edge of the specimen was obviously brittle. The glaze-method oil varnish had a hardness around 4–5, but showed no tendency to flow back. The coloured terpene resin varnish showed a very marked tendency to flow. It apparently had a hardness around 5–6, but this result may have been distorted by the fact that the indent had filled itself up to some extent before it could be measured. (One should note that at the time of these measurements the glazed sample was about a year old while the coloured varnish sample was only six months old. It is possible that both will continue to harden over the next year or two, and will perhaps become more similar.) Finally, the synthetic varnish had a hardness around 6, with no brittle fracture nor any tendency to flow. The fracture surface at the edge of this sample was very rough, presumably because of the particles incorporated in it as a matting agent. It was in fact rather strikingly reminiscent of some of the old Italian ground layers examined previously [5]!

Before discussing the vibration test results, we must examine how these results are to be interpreted. It seems a reasonable approximation to regard the "varnish-affected layer" as a layer of isotropic material with an effective thickness which is not accurately observable (since some varnish material may have penetrated the wood and modified the surface properties) but which is small compared to the thickness of the wood substrate. We can then analyse the influence of the varnish layer as a perturbation to the elastic and damping behaviour of the wood. We first discuss the effect on vibration frequencies. It turns out that two parameters of the varnish layer are significant. One is the mass per unit area — added mass tends to lower all frequencies. The second characterises the stiffness influence, and is the product of the effective Young's modulus and the effective thickness. This "stiffness parameter" governs the tendency for frequencies to be raised by varnish stiffness. The actual shift in any given mode frequency will be a compromise between these raising and lowering tendencies, the precise balance depending on the deformation in the mode in question and the values of the various elastic constants of the wood substrate. There is also a small influence from the Poisson's ratio of the varnish layer, but we will not be much in error if we assume a value 0.3 for this.

The procedure is first to measure the properties of the wood, and then apply the perturbation analysis to interpret the modified vibration frequencies in terms of the varnish stiffness parameter. Because we have only one parameter to determine (the added mass per unit area being known from direct weighing), by measuring more than one frequency we can check the theory by which we are trying to interpret the results. In conventional strip tests, by contrast, there is only one measurement for the one parameter, and it is not so easy to check internal consistency of the interpretation.

The wood properties were determined by the procedure described previously. A typical set of results for the parameters determining mode frequencies are as follows (in the notation of ref. 3):

Density $\rho = 422\text{kg/m}^3$

$D_1 = 750\text{MPa}$, $D_3 = 85\text{MPa}$, $D_4 = 250\text{MPa}$

For the purposes of this exercise it did not seem necessary to cut the samples to different shapes in order to determine D_2: it should be sufficient to assume $D_2 \approx D_3$. The value of D_1 is subject to the errors described earlier: warping may have raised it a bit, while mode shape distortion may have lowered it. However, the general level is quite plausible in comparison with earlier measurements of spruce elasticity. The scatter between the different wood samples before varnishing was non-negligible, even after the rather careful matching process by which the plates were chosen — a range of 7–8% for the stiffnesses was found, but only about 1.5% in the densities.

We now combine this data with the measured frequencies of the lower modes of the varnished plates. On the whole, we obtain reasonable agreement with the theoretical analysis for the relative effects of varnish on the different modes, except that the long-grain bending modes give unreliable results for reasons discussed earlier. The results are not very exciting — all the varnishes produce rather similar effects, with deduced stiffness parameters within a factor of two of each other. The only result worth commenting on is that we see some effects of drying in the coloured terpene varnish sample. This was measured after about six weeks, then again after about six months. In that time the stiffness parameter has increased significantly, by perhaps 70%. The spirit varnish exhibited no such large variations over this sort of time-span, in accordance with the violin makers' experience that spirit varnishes dry much faster than oil varnishes.

Finally, we comment on the damping results. Here we do see interesting differences between the varnishes, and this surely is the area most likely to yield significant acoustical effects of varnish. The point is easily illustrated with some raw data, although in the longer term processing the data by perturbation theory will give more reliable information about the influence of varnish on damping. If we just consider the Q of the lowest cross-grain bending mode, we obtain the following results:

Bare wood: Q = 63
Spirit varnish: Q = 56
Glaze varnish: Q = 45
Coloured terpene varnish: Q = 30 (6 weeks), 43 (6 months)
Synthetic varnish: Q = 41.

Damping variations in this range are something the ear is quite sensitive to: the tap tones of these plates sound quite significantly different. What is needed is to supplement these measurements at low frequency (around 300Hz for this particular mode) with carefully interpreted measurements over a range of frequencies, if possible reaching up into the low kilohertz region where the ear is so sensitive. That might yield some differences between the types of varnish which are perhaps of real perceptual significance.

4. REFERENCES

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