ON THE ACOUSTICAL PROPERTIES OF VIOLIN VARNISH

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Various primers, varnish ingredients, and varnish recipes commonly used in violin making were examined to determine their tonal qualities. The carrier material was spruce cut into 200 strips, both along-grain and cross- grain strips. Measurements were made of the effect of various varnish coatings on two vibration characteristics of the strip—stiffness and damping. The strips were either 2 mm or 3 mm thick, corresponding to the thicknesses found in the violin top plates.

Measurements were made of the eigenfrequencies and damping values of each strip at each coating of primer or varnish. Results are presented as a pseudo velocity of sound (square root of the ratio of stiffness and the mass of the strip) and a loss factor.

Different varnishes and treatments had a substantial effect on stiffness and damping properties of the wood, especially cross-grain specimens. The loss factors η *measured 9 years after treating the strips ranged from 0.89 to 4.1 that of the untreated wood. The velocity of sound* c *varied from 0.92 to 1.27 of the untreated wood. These values take into account a correction that results from measurements of 20 untreated reference strips (also measured after 9 years).*

Measuring Frequency Response Functions and doing modal analysis of a violin before and after varnishing show that the results obtained by the strip method seem to be transferable to the application of varnish to the violin. Accelerance levels of the varnished violin are changed (on average by -2.6 dB), eigenfrequencies are shifted (in a range of $\pm 6\%$*), loss factors change (as much as 75%), and mode shapes are clearly modified in the higher frequency range (1500 Hz).*

Quite often violin varnish is thought to have acoustical consequences that are the secret of violin tone. After comparing the similarities and differences in the workmanship of the old masters, the Hill brothers come to the conclusion that the characteristic timbre of the instruments of the old masters is a result of the varnish (Hill 1963, p. 180). Sacconi reports on instruments of Guarneri del Gesu for which a change in varnish ruined the response (Sacconi 1981, p.154).

In general, varnish serves three purposes—beauty, protection, and tone. This investigation focuses on tone. (Of course, persons applying varnish in the violin maker's workshop should beware of such an unbalanced view. A varnish that shows exemplary acoustical properties is good for nothing if it chips off at the softest touch, or reminds one of shoe polish rather than of a beautiful, brilliant shine.)

A specimen of wood treated with a varnish can have modified elastic properties—stiffness, increased density, and modified damping properties. These changes will be revealed when the specimens are vibrated at their resonance frequencies. Also, the varnish, by closing the surface pores of the wood, can affect the sound radiation of the specimen at higher frequencies.

Method

Carrier Material

The acoustical influence of varnish depends on the carrier material to which the varnish is applied. The effect achieved depends on the way the varnish connects with the surface of the wood. Thus, it is important for the carrier materials to be those used in making violins. The measured effect will also depend on the thickness of the carrier material. The measured effect will understandably be small on a thick wood specimen; whereas, it will be quite large on a thin piece of wood. Because of the anisotropic nature of wood, the effect of the varnish coat will be very different in the along-grain direction of the fibers than in the cross-grain direction.

As a result of these considerations, violin spruce was chosen as the carrier material. Two thicknesses, 2 and 3 mm, were used. Specimens oriented in the along-grain and in the cross-grain direction were prepared. The along-grain strips were 280 mm long and 30 mm wide. The cross-grain direction strips were 130 mm long and 30 mm wide. The frequency of the first free-free vibrating mode was about 250 Hz.

Test Environment and Measurement Uncertainties

The tests were made in an uncontrolled environment—the climate of the mountains of southern Germany. The test specimens all came from the same log which had been carefully seasoned about 7 years. It is known that such seasoning makes the wood less sensitive to changes of climate and humidity.

The purpose of this work was to show the great variations possible in the relative influences of varnish on acoustical properties. All the specimens were tested at the same time under the same conditions. Application techniques were those of a trained violin maker. No additional efforts were made to control depth of penetration, etc. Twenty untreated specimens were tested at the same times.

The measured effects of the varnish treatments were large compared to the changes in the untreated specimens. Mass changes in the untreated specimens were 4 per cent or less, while mass changes in the treated specimens were as high as 12 and 13 per cent. Changes in the ratio of stiffness/mass ranged up to 40% while in the untreated specimens this ratio rarely reached 4%. Changes in the loss factor exceeded +300 per cent in some treated specimens but only +4 per cent (along-grain) or -55 per cent (cross-grain) in the untreated specimens.

From the 20 untreated reference strips correction factors were calculated (Table 3, columns 8 to 11). These correction factors were taken into account in the diagrams, which means that all values of the measured specimens were multiplied by the measured correction factors. (The clear decrease of cross-grain loss factors of the untreated reference strips after 9 years might have been caused by a further drying of the wood and by climate changes). Thus, the results of this work provide some useful information to the violin maker.

Special care was taken to be consistent in the application of each coat of each treatment (painting, wiping, etc.). In order to estimate the degree of uniformity, two strips at a time were used for each treatment in the test of varnish recipes. The diagram values show the average values of the two strips treated identically ("twins"). Although special care was taken to be consistent in the application, Table 3, column 4 to 7, show that there is a considerable difference between the "twins": up to a factor of 0.71 for velocity of sound (along-grain, thickness 3 mm) and 0.55 for loss factor (cross-grain, thickness 2 mm). Comparing the differences of all the "twins" as measured 4 years after the treatment with the differences after 9 years shows that most of the uncertainty is caused by differences in the consistency of application rather than by measurement uncertainties or climate changes.

Differences in the values for two strips treated identically often surpass the value differences among recipes. The fact that there is such considerable difference is of high interest for the violin maker: it shows that in order to achieve a distinct tonal aim there should be taken at least as much focus on *how* to varnish the violin (absorption depth, coat thickness, brush technique, etc.) as on *what* to varnish it with. This observation is also justified by the measurements of different absorption depths as discussed below.

Measurement

A determination of the influence of a selected varnish is possible only if, first of all, the values of the untreated strips are determined, a portion of the untreated strips are then varnished and, after a certain drying period, the values of the treated strips are then compared with the untreated ones.

The strips were softly supported at the two nodal lines of their first free-free bending mode, which was around 250 Hz. Eigenfrequencies and the frequency spread at the half peak points were measured with the help of a structural dynamics analyzer (Hewlett Packard Model 5423A). The strips were excited with a small impact hammer (PCB 086C80). The response was measured with a sound level meter. The transfer function, which is calculated by Fast Fourier transformation software, shows the frequency response curve of each strip. From the eigenfrequency and the half width measurements, properties were determined that are independent of the size of the samples.

Calculation

The formula for the first free-free frequency of a beam of homogeneous material and of constant thickness is

$$f = \frac{3.8}{\sqrt{12}}\sqrt{\frac{E}{D}} \times \frac{h}{L^2}$$

where f = frequency
E = Young's modulus of elasticity of the material
D = density
h = thickness
L = length

The second term contains the critical dimensions of the beam. The first term, the square root of the material stiffness divided by the material density, describes the dependence of the frequency on the properties of the material. An assumption is made that the change in dimensions of the specimens when the varnish is applied will be so small that it can be ignored. An assumption is also made that the changes caused by the varnish application can be properly described and evaluated by calculating an equivalent square root of E over D as though the varnished wood specimen were homogeneous. Since the test models the actual vibrating situation in the violin, this simplifying assumption still permits relative comparison of varnishes on a realistic basis. The test results are presented as changes to the velocity of sound, calculated as described above. The velocity of sound of the untreated strips varied from around 5000 m/s to 6200 m/s in the along-grain strips and from 1000 to 1600 m/s for the cross-grain strips.

The loss factor is a measure of the absorbed energy per cycle of vibration to the total energy in the vibrating strip. It can be determined by the width of the resonance peak: the narrower the peak the lower the loss factor. Common practice is to measure the width of the resonance peak at the point where the energy in the vibrating system is one half that of the peak energy—minus 3 dB when the energy is plotted on a logarithmic scale. The loss factor is the ratio of the frequency width at the minus 3 dB position to the peak frequency. It is directly proportional to the percent loss of amplitude per cycle that the vibrating strip would lose if the vibration were decaying naturally. The loss factor for the untreated strips varied from 0.005 to 0.007 in the along-grain strips and from 0.017 to 0.021 in the cross-grain strips.

Tonal Interpretation of Acoustical Modifications

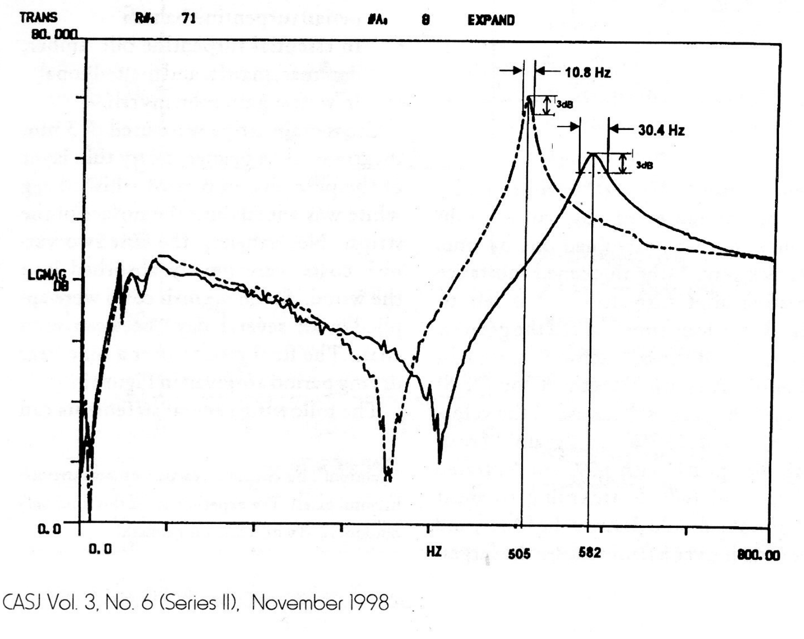
The velocity of sound is an important indicator of the acoustical quality of a vibrating material. A violin plate made of wood with high velocity of sound has a higher ratio of stiffness to mass than one with a low velocity of sound. This means that the target resonance goals, for example, tap tones, can be achieved with smaller thicknesses and, therefore, with less weight. Such a violin plate will be easier to excite and will produce a greater radiation of sound. A logical goal for varnishing is to try to improve the ratio of stiffness to mass. Such an improvement will be indicated by an increase in the eigenfrequency of the strip.

Establishing a target for the desired loss factor is a more difficult process. One must decide in this case which tonal characteristics one wants to emphasize and which to reduce. A decrease in loss factor increases the amplitudes of the vibration peaks of the instrument but also makes them narrower. A varnish that causes such a decrease of damping when applied to an instrument will increase efficiency and promote a louder but possibly unbalanced sound; whereas, an increase of damping broadens the resonance peaks so that dips in sound between resonance peaks are not so deep. The sound level will be reduced but the sound will be more balanced and the instrument may respond more easily. A study by Lottermoser (1958) describes the dependence of eigenfrequencies on loss factors and on transient phenomena.

An Introductory Example

The first example gives an idea of how much the resonance properties of a cross-grain spruce strip of 3 mm thickness can be modified by several thin coats of a solution of resin in turpentine oil (see Figure 1). When the spectrum of the untreated wood (dashed line) is compared with the spectrum of the varnished wood (solid line), one finds that the eigenfrequency rose from 505 Hz to 582 Hz, increasing the calculated velocity of sound by 15.2% from 1343 m/s to 1548 m/s.

Figure 1 ▪ Changes of resonance properties of a spruce strip (3 mm thickness, cross-grain) caused by a turpentine-oil varnish. Dashed line: Frequency Response Function (FRF) of untreated strip. Solid line: FRF of varnished strip.



Also, the half width at the -3 dB has increased, the peak amplitude has decreased, and the calculated loss factor has increased by 144% from 0.0214 to 0.052. This varnish treatment had an extreme damping effect.

Primer

The primer is in a different category from the varnish. It is absorbed into the pores of the wood. The varnish, applied after the primer, lies on the surface of the wood. The following substances were investigated as primers:

- alizarin in alcohol, bone glue, egg white, Greek pitch, lixivinum (NaOH), nitric acid, propolis in alcohol, synthetic resin, and water-glass.

Several oils were also tested as primers:

- almond oil, grape seed oil, jojoba oil, linseed oil, peanut oil and poppyseed oil.

Those primers that were wiped on were done with a cloth. The application was repeated after four months. The test data were taken after a drying period of four and nine years. Figure 2 shows the percentage change in velocity of sound and loss factor for both cross-grain and along-grain strips.

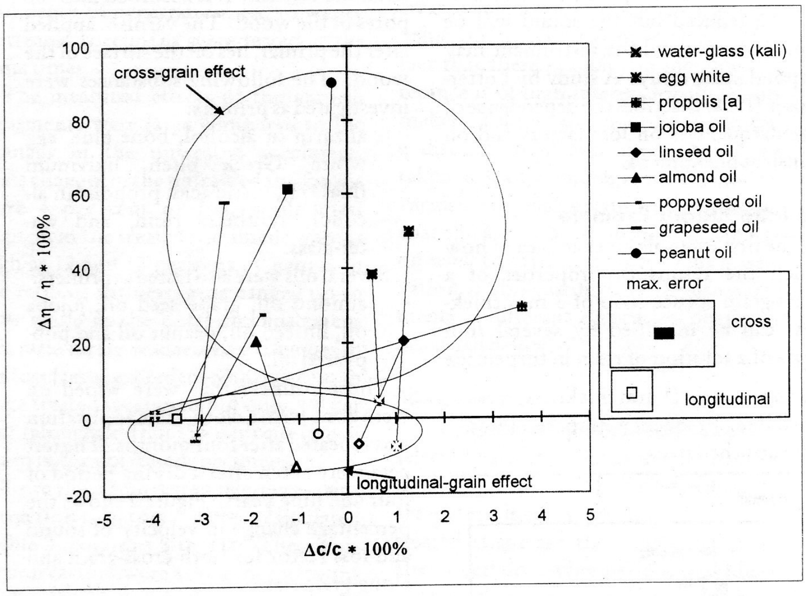
In general the changes in cross-grain strips are far more significant than those in the along-grain strips. The loss factor changes much more than velocity of sound. In general, the effects of the oils are quite similar. There is a strong increase in the cross-grain fiber loss factor. The velocity of sound in the along-grain fiber direction was significantly reduced.

In Figure 2 the data points for cross-grain and along-grain strips for each substance are connected with lines: the angle of gradient shows the change of the spruce's anisotropy. In untreated (German) spruce the velocity of sound along the grain (average about 5500 m/s)

Figure 2 ▪ Influence of various primers on "velocity of sound" *c* (horizontal scale) and loss- factor η (vertical scale) of spruce strips with a thickness of 3 mm. Effect on cross-grain strips: black data points, effect on longitudinal-grain strips: white data points. All measurements nine years after treatment.
It shows that

- the cross-grain effect is clearly higher than the longitudinal-grain effect
- the effect on loss-factor η is clearly higher than on velocity of sound *c*.
- the grain-directional anisotropy of η increases with priming the wood.
- in most cases the grain-directional anisotropy of *c* decreases with priming the wood. This is due to the stiffening effect in cross-grain direction of the wood. The degree of decreasing *c* anisotropy depends highly on the primer used.

For example: While propolis in alcohol [a] causes a cross-grain increase of *c* of 3.6 percent and at the same time an along-grain decrease of *c* of -4 percent, peanut oil causes -0.3 percent cross-grain decrease and -0.6 percent along-grain decrease of *c*.



is 3.5 times as high as across the grain. The loss factor in the cross-grain direction (average about 0.022) is 3 times as high as along the grain.

The primers shown in Figure 2 in general cause an increase of the grain-directional loss factor anisotropy. Furthermore, it shows that in most cases the grain-directional anisotropy of the velocity of sound decreases with priming (and varnishing) the wood. This is due to the stiffening effect in the cross-grain direction. The extent of the decrease in the anisotropy of velocity of sound depends considerably on the primer used.

The influences of the various substances must be examined one by one. "Greek pitch" (the thickened substance existing after turpentine oil is left to stand for a long time) caused the greatest increase of loss factor cross-grain (104%). A synthetic resin (Clou DDS) caused the greatest increase in the velocity of sound (16.7%) cross-grain. Treating the spruce with 65% concentrated nitric acid (which according to most textbooks should destroy the fibers) and heating it over a flame causes the largest increase in along-grain velocity of sound, 2.3%[1]. At the same time this acid treatment causes the largest increase of along-grain loss factor, +65% four years after treatment which fell to +35% after nine years. The increase of along-grain velocity stayed constant over this time.

The influence of absorption depth into the wood

The difference between wiping the primer on the wood and soaking the strip was explored using linseed oil and water glass. The cross-grain loss factor was strongly increased by soaking. (See Table 1.)

This experiment indicates that soaking wood in a primer should be used only when a drastic decrease in stiffness and increase in damping is intended.

Resins

The main ingredients of violin varnish are resins dissolved either in alcohol, essential oil, or fatty oil. Most varnish recipes use several resins. However, a base line series of tests was to try one resin at a time in the appropriate vehicle. In each case 2 grams of resin was dissolved in 10 ml of solvent. The following resins were selected:

- In alcohol: alizarin, arabicum gum, benzoin, colophony, copal, juniper gum, propolis (the resin produced by bees), sandarac, shellac, and Venetian turpentine-balsam
- In essential turpentine oil: amber, dammar, mastic, and melted copal
- In water: gum resin myrrh.

Cross-grain strips were used of 3 mm thickness. As a primer, a very thin layer of the precipitated part of whisked egg white was wiped onto the surface of the strips. Nevertheless, the first two varnish coats were mostly absorbed into the wood. Seven varnish coats were applied with several days between each coat. The final results after a nine year drying period are given in Figure 3.

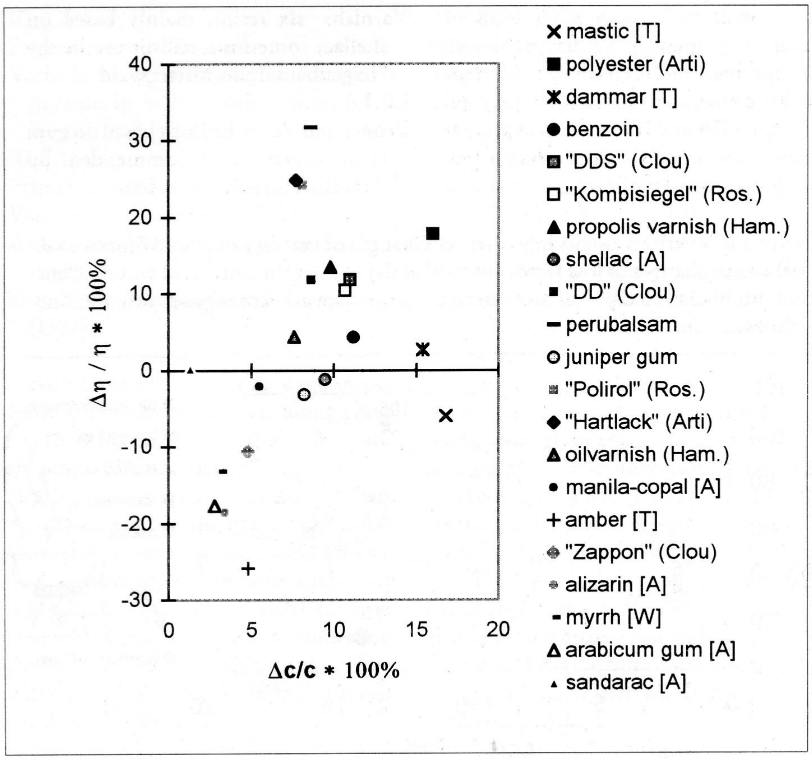
The following general statements can

[1]Caution! This chemical reaction causes *extremely* harmful gases! Try experiments of this kind only outdoors and with a suitable gasmask!

Table 1 ▪ The influence of absorption depth into the wood
Spruce strips, thickness 3 mm, treated 1988. Changes against the untreated wood in per cent measured 1997 (1994)

Measurement	Grain Orientation	Substance	Soaked	Wiped
loss factor	cross	linseed oil	+333 (+372)	+20 (+41)
loss factor	cross	waterglass	+56 (+41)	+8 (+5)
loss factor	along-grain	linseed oil	+15 (+2)	-7 (+9)
loss factor	along-grain	waterglass	+37 (+52)	+28 (+5)
velocity of sound	cross	linseed oil	-8.4 (-6.4)	-0.3 (+0.2)
velocity of sound	cross	waterglass	-1.8 (-1.4)	+0.5 (+0.1)
velocity of sound	along-grain	linseed oil	-5.6 (-5.3)	-0.3 (+0.2)
velocity of sound	along-grain	waterglass	-1.1 -1.0	+0.1 (+0.5)

Figure 3 ▪ Influence of various resins (six coats each) on "velocity of sound" c (horizontal scale) and loss-factor η (vertical scale) against the untreated wood. All measurements nine years after varnishing. Note that those resins dissolved in turpentine oil [T] need a much longer drying period (several years) to reach the plotted values than those resins dissolved in alcohol [A]. Strips: spruce cross-grain orientation, thickness 3 mm.



be made about the results:

- The resins dissolved in essential oil cause a higher increase in mass than those dissolved in alcohol—up to 7% increase compared to an average of about 1%. In some cases (alizarin, Arabicum gum, and even juniper gum and myrrh) there was a reduction of mass within the drying period, perhaps due to chemical action and evaporation.
- The resins dissolved in essential oil (mastic, dammar, and melted copal) still cause a distinct increase in the loss factor of more than 50% compared with the untreated wood after a drying period of 4 years; whereas, after 9 years a considerable decrease of loss factor can be observed. This indicates the long-time effect of essential oil as a solvent.

  Amber dissolved in turpentine oil is an exception. In contrast to the other resins dissolved in essential oil, amber causes a decrease of loss factor of -11.3 % after four years drying, and a decrease of -25.6% after nine years drying compared with the untreated cross-grain strip (3 mm thickness). The strips varnished with resins dissolved in alcohol showed a decrease of loss factor even within a few days.

Several synthetic resins were tested and compared with the traditional natural resins. The average increase in mass was about 3%. The velocity of sound increased in every case with the greatest being polyester with +16.0% after 9 years drying (+15.0% after four years) down to +4.8% (+4.1%) for Zappon. The loss factor varied from +11.8% (28.4%) for DD to -10.6% (-9.1%) for Zappon. The loss factor varied from +11.8% (28.4%) for DD to -10.6% (-9.1%) for Zappon.

These resins are clearly not as interesting as the natural resins, for the range of property variations is not as great in any category. Therefore, they offer the violin maker less freedom of choice in his work on tone formation.

In all test cases, the influence of the resin increased with the number of coats. In those varnishes with alcohol as the solvent the influence of the first two

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coats is clearly greater than that of the subsequent coats.

Components in the Complex Recipes

It was astonishing to find that the effect caused by the ingredients individually did not necessarily correspond with the effect caused by a varnish made out of several of these ingredients. The effect is very obvious in an essential oil varnish that is sometimes used at the Geigenbauschule Mittenwald. It consists of melted copal, dammar, and mastic cooked in oxidized turpentine oil with a small amount of linseed oil. (See Appendix B). All of these ingredients have an extreme effect on damping when applied separately, yet the varnish made from the above ingredients causes little change in damping. (Note that the varnish was stored for several years before application, which is advisable for all essential oil varnishes.) Figure 4 shows the effects of the ingredients (grey data points) compared to the effect of the varnish, both after 4 years of standing after application. In the first months after application, there was even a decrease in loss factor!

In general, it appears to be easier to predict the performance of an alcohol varnish from the performance of its components than the performance of an oil varnish.

There seems to be an obvious reason for the clearly different acoustic effects of single component versus complex recipes, as well as for the enormous differences among various essential oil varnishes; namely, the process of making the varnish. Many resins that are used for essential (as well as fatty) oil varnishes must be melted before cooking. This is particularly true for the Venetian turpentine used in the "Sacconi" varnish. My experience with melting Venetian turpentine (as well as larch resin) is that the mechanical properties of the cooled resin are highly dependent on the melting temperature and cooking time. The unmelted resin has the consistency of honey. If the resin is melted at 120°C and afterwards cooled, it still will be soft and flexible. If melted at about 140° C and cooled, the resin can be bent slowly, but it will break if it is bent fast. If melted above 170°C, it will always be brittle. Both the acoustical and also the mechanical properties (such as flaking-off or keeping permanent fingerprints) of varnish cooked of such resins depends highly on the melting conditions—temperature, melting time, shape of the melting pot, frequency of stirring. All these alter the *temperature profile* of the melted resin and thus its properties when later used as a component of the varnish. If one allows different temperature-layers in the melting process, it is even possible to obtain a combination of properties out of the same resin. Many ancient striking remarks in historical varnish recipes such as the kind of fire, a very certain shape of pot, time of stirring, etc. seem to have a very sensitive background. Certainly the recipe itself is only half of the truth.

The violinmaker must carefully watch the melting and cooking process of his varnish in order to achieve constant acoustic results. Finally, only test measurements (such as carefully listening to the tap tone of varnished wooden strips) will make sure what kind of acoustic properties he has achieved. Comparing the extremely different acoustic effects of the two essential oil varnishes IIA and IIB in the next section shows that there is a wide acoustic palette for treating a violin.

Concerning this challenge (and at the same time danger), alcohol varnishes are far less complicated because they are more calculable. But as it is possible to get or even surpass their acoustic properties with essential oil varnishes and especially because of their visual attractiveness, the author prefers to use essential oil varnishes for his instruments.

Varnish Recipes and Results

Some simplification is necessary because of the enormous number and variety of possible and recommended recipes. From both an historical perspective and from acoustical property perspective a classification has been made into three groups.

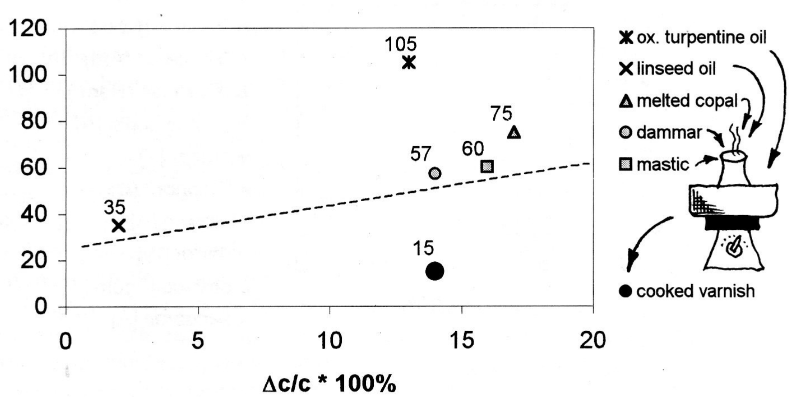
I. Alcohol varnishes
II. Essential oil varnishes, e.g. turpentine oil
III. Fatty oil varnishes, e.g. linseed oil

For Group I - three examples were chosen of resins dissolved in alcohol:

I.A.1
Primer: bone glue, historically used in Mittenwald
Varnish: six resins, mainly based on shellac; sometimes still in use in the Geigenbauschule, Mittenwald

I.B.1
Primer and Varnish: Both based on gum resin myrrh as recommended by Aracelian (1965)

Figure 4 ▪ A varnish and its ingredients. Changes of velocity of sound (horizontal scale) versus changes of loss factor (vertical scale) against the untreated wood. Data point numbers: changes of loss factor. Strips: spruce cross-grain orientation; thickness 3 mm.



I.C.1
Primer: casein as sometimes used as a ground for painters
Varnish: ready-made "Retouchierlack" by a violin varnish dealer

For Group II - two examples were chosen of resins dissolved in essential oil:
II.A.1
Primer: sandarac in oil of lavender - according to Bonnani (Rome 1713)
Varnish: mastic, dammar and melted copal with a little linseed oil added to the turpentine oil, in use in the Geigenbauschule, Mittenwald
II.B.1
Primer: waterglass and "white varnish" with the liquid part that settles when beaten egg white is allowed to stand for two hours. (For the influence of beaten egg white, see Figure 2 data point "egg white").
Varnish: propolis and Venetian turpentine, dissolved in spike oil, both as recommended by Sacconi (1981)

For Group III - two examples were chosen of resins dissolved in fatty oil:
III.A.1
Primer: warm walnut oil
Varnish: colophony and Venetian turpentine in walnut oil: taken from Baese (1987) ("Zanetto")
III.B.1
Primer: linseed oil with bone glue
Varnish:
a) mastic and venetian turpentine in linseed oil.
b) amber in linseed oil. both from Baese (1987)

All of the combinations were tested both on cross-grain and along-grain spruce strips of both 2.0 and 3.0 mm thickness. Two coats of all primers were applied a week apart. Six coats of varnish were applied for the Group I and Group II. Four coats of Group III varnishes were applied because each coat was thicker. For varnish IIIB1 the first coat was varnish IIIBa and the following three coats were varnish IIIBb. The author used ultra violet lights to speed the drying cycle.

Figures 5a to 5d show the changes of velocity of sound (horizontal scale) versus the changes of loss factor (vertical scale) for the varnished strips compared to the untreated four spruce strip types (along-grain and cross-grain orientation; 3 mm and 2 mm thickness) as measured after a drying period after varnishing of four years (white data points) and nine years (black data points). Several points can be made by studying the results.

Acoustical Properties: Enormous differences in the acoustic properties are possible by selecting appropriate varnish applications. The data suggest a range of loss factors from -12% (varnish IB) to +306% (IIB) cross-grain and from -10% (IB) to +88% (IIB) along-grain. The velocity of sound changes from -3.1% (IIIA) to +26.7% (IC) cross-grain and from -8.3% (IIIB) to no change (IB) along-grain.

Comparing the four years changes with those after a nine year drying period, all varnishes (with one exception) have the tendency to further decrease loss factor and increase velocity of sound (and thus stiffness)—see the angle of gradient of connection lines between white and black data points. This decrease of damping and increase of stiffness is even clearly correct for the fast drying alcohol varnishes (group I), as can be seen by the considerable lengths of connection lines. The further drying and hardening of alcohol varnish has pushed the loss factor to -10% (IB; along-grain; 2 mm) after nine years from +2.6% after four years drying. And the high damping of IIIB at +246% (cross-grain, 3 mm) after four years has fallen to +185% after nine years of drying.

Stiffness: All varnishes *reduce the anisotropy* of the wood as they stiffen the wood cross-grain and weaken the wood along-grain. (The only varnish which weakens the wood cross-grain (IIIA) weakens still more along-grain). It is not possible to predict the stiffness effect in one direction by knowing the effect in the other direction: Varnish IC causes a clearly higher cross-grain stiffening than IA but at the same time reduces stiffness along-grain more than IA. It is the same with IIIB and IIIA.

Loss factor: All varnishes *increase anisotropy* by a factor of about 3, as they increase loss factor cross-grain three times as much as along-grain. (The vertical scale of Figures 5c and 5d had to be widened by a factor of 3 to give the data points about the same vertical diagram positions as in the along-grain diagrams Figures 5a and 5b.

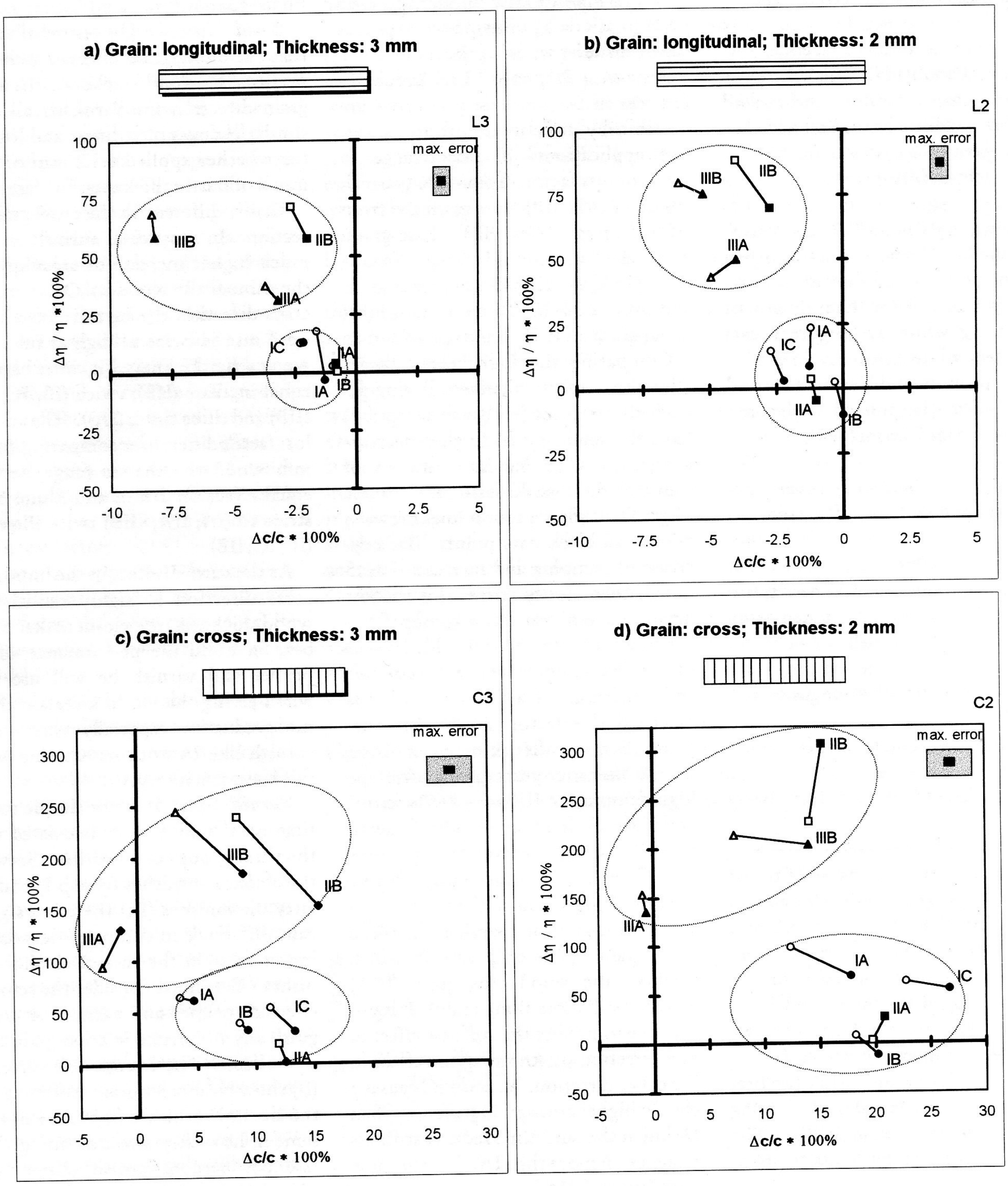
Wood thickness: The test results show that the along-grain effect is rather insensitive to wood thickness. In along-grain direction the varnishes all cause similar changes of stiffness and loss factor whether applied on 2 mm or on 3 mm wood strip thickness.

This is different in the cross-grain direction. In most cases varnish causes a much higher increase of cross stiffness the thinner the wood is. On average in cross direction the increase of stiffness on 2 mm is twice as high as on 3 mm wood strip thickness. (It varies between equal increase (IIB), twice (IB; IC; IIA; IIIB) and three times (IA)). The affected loss factor differences comparing 2 and 3 mm wood thicknesses range between equal effect on 2 mm and 3 mm thick strips to (IA; IIA; IIIB) twice the effect (IB; IC; IIB).

As the varnish effect in the important cross direction is highly sensitive to wood thickness, the violin maker has to bear in mind the performance of the primer and varnish he will use later when giving the violin a certain thickness graduation, especially when using a varnish like IA with its extreme wood thickness sensitivity.

Varnish types: It is not simple to distinguish the differences associated with the three groups of varnishes. Between the alcohol varnishes (group I) and the fatty oil vanishes (III) there is a significant difference in damping: less damping increase in the case of alcohol varnishes. One must consider the separate effect of primer and varnish to distinguish any difference in cross-grain stiffness effects. The essential oil varnishes (II) show clear cross-grain stiffening like the alcohol varnishes (I) but are not the same in how they affect damping. The essential "Sacconi varnish" (IIB) on that score acts like the fatty oil varnishes while the essential mastic-dammar-

Figure 5 ▪ Influence of various varnishes on "velocity of sound" *c* (horizontal scale) and loss-factor η (vertical scale) of thin spruce strips. Changes in percent against the untreated wood for four years (white data points) and for nine years (black data points) afler varnishing. Strip type: a) along-grain, thickness of strip: 3 mm; b) along-grain, 2 mm c) cross-grain, 3 mm; d) cross-grain, 2 mm. Note different scale for along-grain and cross-grain. Alcohol varnishes (IA - C): circular data points; essential oil varnishes (IIA, B) quadratic data points; fatty oil varnishes (IIIA, B): triangular data points.



copal varnish (IIA) affects damping like the least damping alcohol varnishes. The supposed reason for the enormous acoustic differences of different essential oil varnishes was already mentioned. The same Sacconi-recipe can likely deliver an acoustically completely different varnish if the melting process is modified, especially as some of its ingredients are characterized by the sensitivity to melting temperatures—the same might also be true for the fatty oil varnishes IIIA and IIIB. Melting the Venetian turpentine at slightly higher temperature would shift the acoustics of the finished varnish more in the direction of IIA. The wide bandwidth of acoustic effects is the reason why the essential oil varnishes fit to either of both groups, (surround with dotted lines in Figure 5).

Is it the ground or is it the varnish?

There is wide spread disagreement whether the primer (the substance being absorbed by the wood) or the varnish covering the surface is primarily important for determining acoustical properties. Sacconi (1981) remarks that if it were the varnish, the acoustical quality would have been equal for all the Cremonese makers in any one period of time. He further observes that Stradivarius instruments with only a little varnish left exhibit the same sound qualities as those that have not been touched. He concludes that it must be the primer that influenced the sound. However, his observation of Guarneri instruments whose response was ruined after the varnish was changed speaks for the importance of the varnish. Charles Beare (1992) does not think that the top varnish of the old Italian instruments has much effect on the tone. For him "the ground is absolutely of crucial importance."

The results reported here on these specific varnish compositions show that there is not a uniform answer to the priority of primer or varnish. In general, the varnish contributed significantly more to the increase of cross-grain stiffness and the decrease of along-grain stiffness than the primer used. In the extreme case, varnish IC, the factor is roughly five-fold. In the case of the loss factor the effect of the various types of varnish is mixed. There is a case (IA) where most of the loss comes from the varnish; there is the opposite situation (IIA) where the primer is the greatest influence; and cases IIB and IIIB where both primer and varnish contribute strongly to the loss factor. When one considers also the test results from primers alone and from single component varnishes, it becomes obvious that there is an enormous freedom to adjust the degree to which primer and varnish provide the final acoustic result.

Table 2 ▪ Eigenfrequency shifts of two white violins and a white cello in per cent caused by varnish (6% corresponds to one semitone)

Instrument	Mode A_0	Mode C_2	Mode T_1	Mode B_1
Violin "Phil. 4,7"	-2.1	+2.9	+5.0	+2.9
Violin "Dan. 6,28" see Figure 7	+1.7	+4.0	+2.9	+1.4
Cello	0	+2.0	+2.6	+2.8

There are important practical consequences from choosing either the primer or the varnish to accomplish a desired result. If the varnish, but not the primer, is the principal influence on the acoustical properties, it will be easy to regulate the tonal effect by the thickness and the number of coats. However, the performance of such an instrument will be very sensitive to eventual wear of the varnish or to touch-up modifications. (This may have been the case in the Guarnerius violins mentioned by Sacconi.) If the main influence is caused by the primer, the results will be very difficult to control. The acoustical influence of absorption in some cases depends on the thickness graduations of the wood. This must be taken into account as the violin in the white is constructed. Such an instrument, in which the "secret" of the varnish is in the primer, will be insensitive to the wear of the varnish. A further challenge to the application methods of primer and varnish might be to apply both selectively over the surface of the body to achieve certain desired eigenmode modifications.

The Drying Process

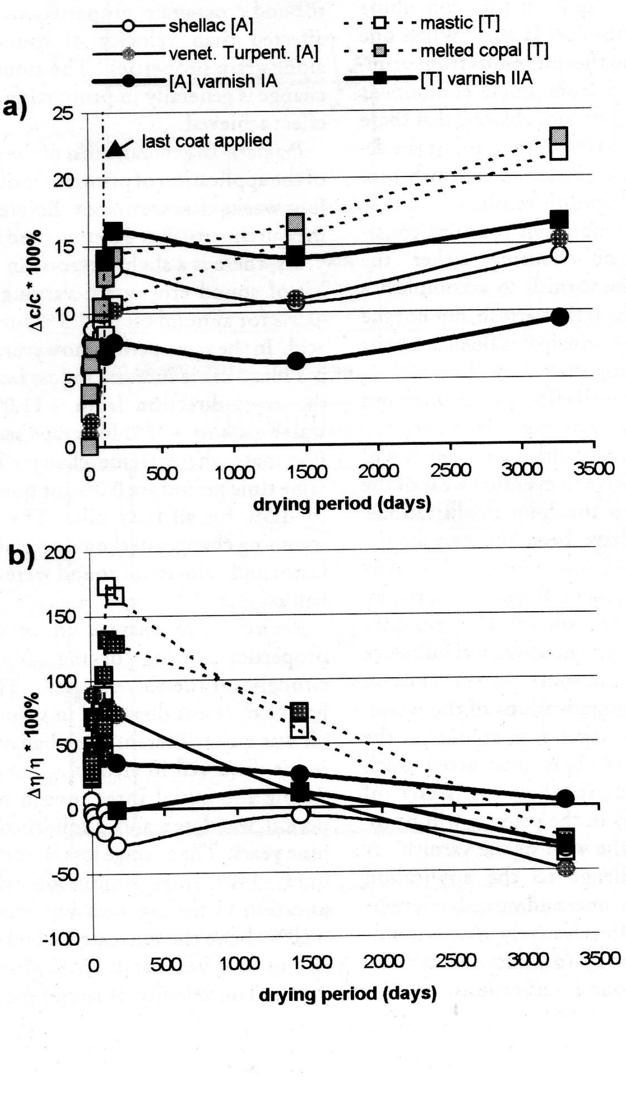
A comparison of the measured acoustical properties directly after the treatment, some months later, and after a drying period of four and nine years shows that in some cases there are remarkable trends. In general, the loss factor and cross-grain properties are more affected than velocity of sound and along-grain properties. The amount of change is generally in proportion to the effect achieved.

Primers: In general, most of the effects of the application of primers are obvious four weeks after treatment. Between the measurements after 8 months and after 4 years, there is a slight decrease in velocity of sound cross-grain varying from -0.5% for almond oil to -2.5 % for nitric acid. In the same period, however, there is a remarkable increase in loss factor in the cross direction from +11.0% for water glass to +38% for grape seed oil. For mass, the extreme changes in the same time period are 0.0% for bone glue to -1.5% for all fatty oils. The corresponding changes in the along-grain loss factor and velocity of sound were about half as great.

Resins: The changes in acoustical properties during drying depended strongly on the solvent used. The behavior of resins dissolved in turpentine oil was quite different from behavior of resins dissolved in alcohol. The effect during the initial three month testing period was large and diminished over nine years. The average loss factor measured +140% three months after the application of the last coat but was only +60% above the untreated wood at the end of four years and +51% after nine years. The velocity of sound increased over the years. For example, mastic in turpentine oil had an increase in velocity of sound compared to untreated wood of +10.8% after two months, +15.4% after four years, and +21.7% after nine years. Obviously the physical and chemical changes have a long term effect on the acoustical properties. The sound of an instrument with this kind of varnish will probably be different after a few years. It is not clear whether the change has stabilized in only nine years.

The resins dissolved in alcohol showed a different influence with regard to the velocity of sound. In most cases the loss factor effect measured immediately after varnishing was reduced somewhat with prolonged drying. With other resins such as colophony dissolved in alcohol the loss factor reaches a stable value in a short time.

Figure 6 ▪ Drying process of various resins and varnishes on cross-grain spruce strips with a thickness of 3 mm: Alcohol varnish (IA) and two of its ingredients (shellac, Venetian turpentine) dissolved in alcohol; essential oil varnish (IIA) and two of its incredients (mastic, melted copal) dissolved in turpentine oil. a) Changes of velocity of sound relative to the untreated wood in percent. b) Changes of loss factor relative to the untreated wood in percent. Drying period in days. Six coats applied, first coat: zero; last coat: 90 days. Note different vertical scales.



Recipes: Figure 6 shows the drying process of alcohol varnish (IA) and essential oil varnish (IIA) and respectively two of their ingredients (shellac and Venetian turpentine in alcohol; mastic and melted copal in turpentine oil), showing the raw data (without climate correction).

The lengthy drying performance of mastic and melted copal as examples for resins dissolved in turpentine oil is obvious. Immediately after applying the last of six coats the loss factor increase for mastic is 172% compared with the untreated wood and 132% for melted copal. With further drying the loss factor decreases, to fall below zero after 6 to 7 years. At the same time the velocity of sound (which can be measured very precisely) increases. This process might not yet be stopped. In contrast to this drying performance, the varnish (IIA) made by these ingredients does not cause any increase of loss factor even shortly after applying the last of six coats and causes an increase of 14.1% of velocity of sound relative to the untreated cross-grain strip. All substances and varnishes in common have an inverse development of loss factor and velocity of sound within the drying process.

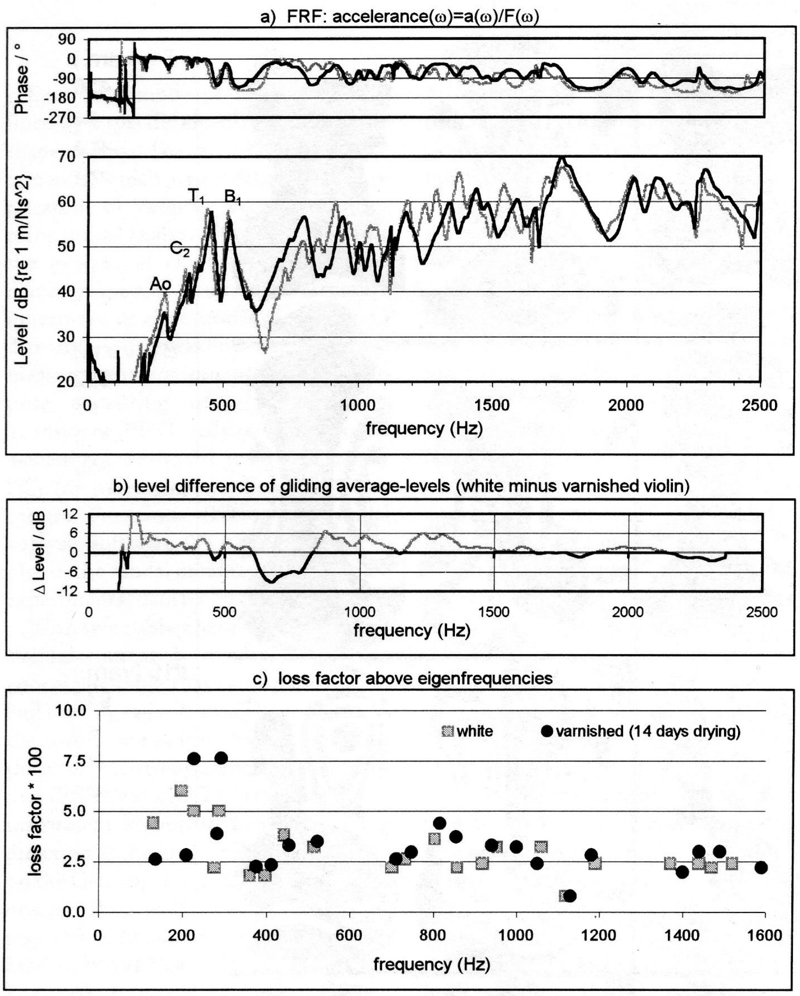
In general—as is also obvious by the examples plotted in Figure 6—the changes during drying seem to be significantly more stable with complex recipes (like IA, IIA) than with the single resin solutions described earlier. And although there are very obvious performance differences in the drying process of single resins depending on the solvent used, the varnishes show very similar drying performances independently of their solvent (Figure 6 shows that IA and IIA—although having different absolute effects—run quite parallel in the drying period).

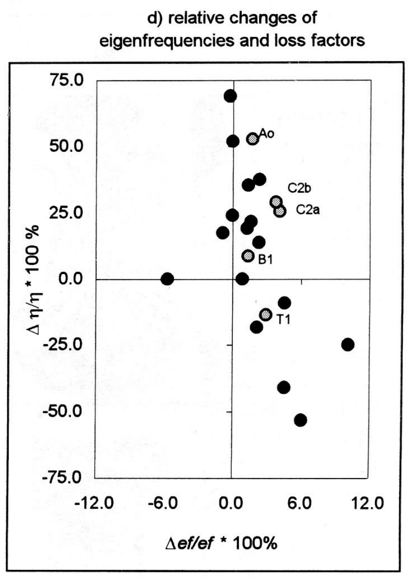
Application to the Instrument

The acoustical influence of violin varnish being applied to the instrument can be measured indirectly by measuring the acoustical properties of the violin before and after varnishing. The acoustical properties of the violin are deter-

Figure 7 ▪ Application of essential oil varnish (similar to IIA) on a violin. Both white and varnished with damped strings; without chinrest. Soundpost stayed in the instrument while varnishing.

d-TAC-Project	Instrument	Sett.	attrib.	date
Z4 442+x/442-x	violin "Dan.6,28" with strings	FRF1	white	1998-08-13
Z5 442+x/442-x	violin "Dan.6,28" with strings	FRF1	varnished	1998-09-02





a) frequency response function (accelerance) measured with accelerometer and impact hammer (both at bridge). Grey line: white violin. Black line: varnished violin (only 14 days drying period, 80h ultraviolet light).
b) level differences of moving average accelerance-level (calculated from FRFs Figure 7a: white minus varnished violin.
c) loss factors, η (absolute values) above eigenfrequencies *of corresponding eigenmodes* by curve-fitting peaks of frequency response function (see text).
d) relative changes of loss factors η and eigenfrequencies ef of corresponding eigenmodes of varnished violin against white violin in per cent.

mined by its definite eigenmodes. These eigenmodes result from the individual stiffness-mass-damping distribution of the constructed violin. As this distribution of stiffness, mass and damping results from construction (including treatment) and material properties, the eigenmodes of vibration are a *synthesis of the sum of all of the violin's construction and material parameters.* Furthermore, the individual eigenmodes are the *acoustical reason for the definite tone* of the instrument, as they determine the radiation of sound and the response of the instrument. This is why an analysis of eigenmodes can be a sensible connecting link between the making and the tone of the instrument:

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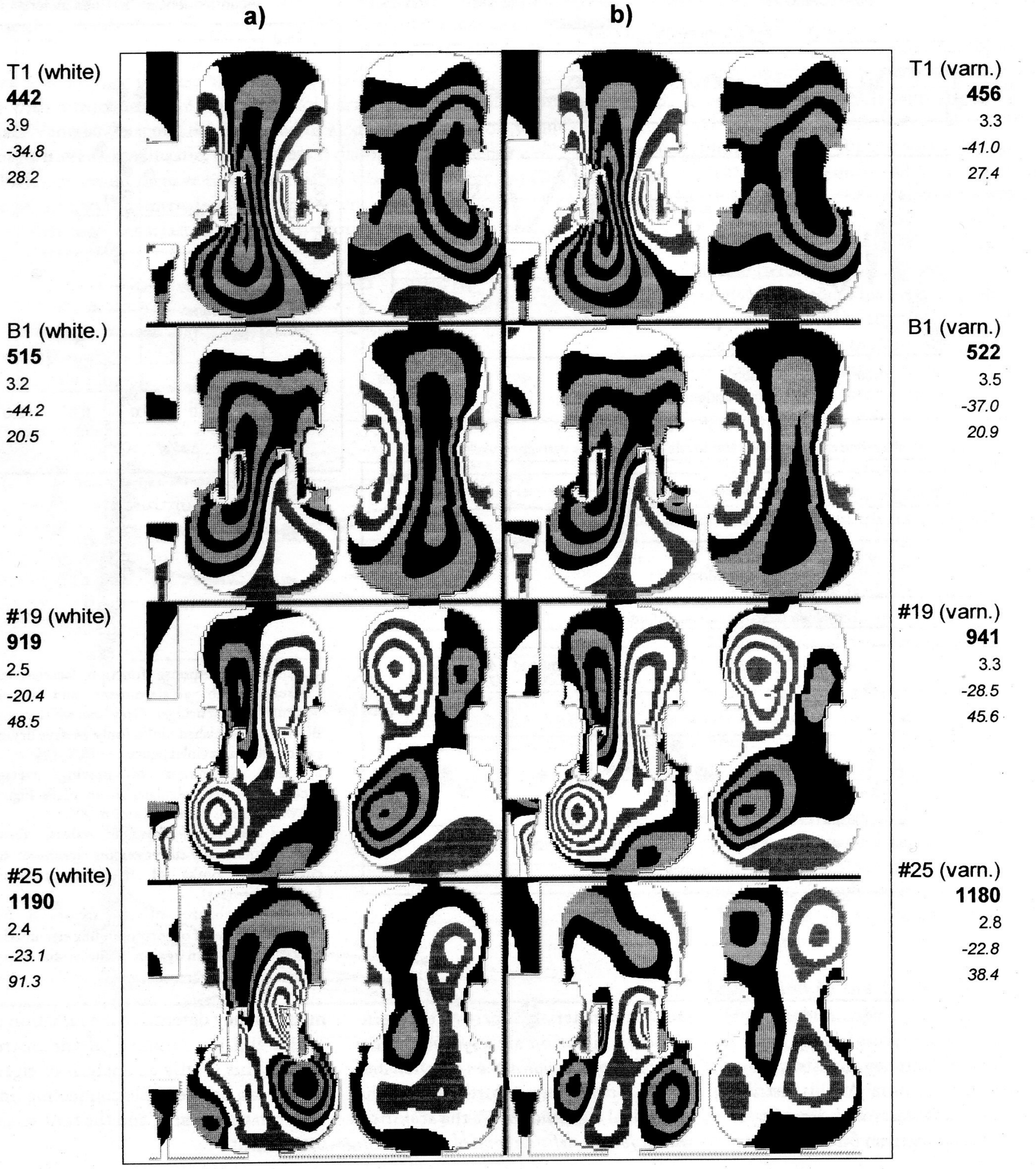
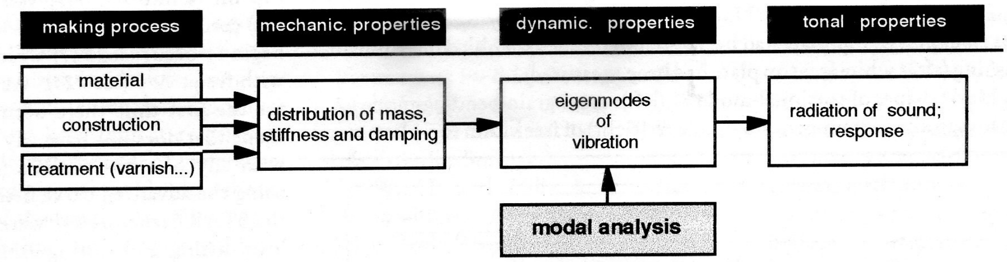
Figure 8 ▪ Modal analysis of a white (a) and varnished (b) violin. Four representative mode shapes (scaling: mobility, calculated from accelerance-residues divided by $2\pi*f$). Each mode shape is represented by tailpiece and fingerboard (left) top plate (middle) and back plate (right). Both plates are shown from the outside. Phase convention: all parts of the corpus expanding at the same time are defined as in phase and plotted with same pattern-type; i. e., white-gray; compressing parts are black-gray. Absolute mobility-difference between two lines of same kind (white-white or black-black) = 10 (Hz*m) / (s*N). Number beside mode shapes (from top to bottom): mode-name or mode-#; frequency (Hz); loss factor (%); *maximum negative magnitude* (Hz*m) / (s*N); *maximum positive magnitude* (Hz*m) / (s*N)





Each eigenmode of vibration is defined by a specific eigenfrequency mode shape and loss factor. These modal parameters, which are modified by the application of varnish, were determined using modal analysis. (Modal analysis is the process of characterizing the dynamic properties of an elastic structure in terms of its eigenmodes of vibration.) The author's workshop has acoustical measurement equipment for this purpose consisting of a Fast-Fourier-Transform (FFT) analyzer (difa FA-100 4-channel-DSP-Board in a Pentium II PC) for measuring the Frequency Response Functions (FRF) and modal analysis software (STAR Structure) to obtain the modal parameters from these experimental data by "curve-fitting."

With two rubber bands (length 60 cm) the instrument is free-free laid on a coordinate-table that can be moved on ball bearing rails. A small laser points to the coordinate points that are one after the other excited by a small impact hammer (PCB 086S80). The response of the instrument is measured in the bowing direction at the upper edge of the bridge on the G-string side with a small accelerometer (PCB 352822; 0.5g). From the response-excitation-ratio at 467 coordinate points, 595 FRFs are calculated. For overview measurements such as Figure 8 and 9, they are reduced to 125 FRFs.

Figures 7 to 9 show the modification of the violin's eigenmodes caused by the varnish with respect to changes of a) level differences, b) eigenfrequencies, c) loss factors, d) mode shapes. During varnishing the sound post stayed at its defined position in the instrument.

Fig 7a shows the FRF of the violin before (gray line) and after varnishing (black line). The eigenfrequencies appear as peaks, having a certain frequency, accelerance-level (absolute values re $1 m/Ns^2$) and bandwidth. The effect of varnish (mainly for the higher modes) is very obvious.

Level differences: the accelerance-level is considerably decreased by the relatively fresh varnish. Figure 7b represents the level difference (white minus varnished violin) of moving-average levels (bandwidth one semitone) calculated from the FRFs Figure 7a. At this point of the drying process (only 14 days after applying the last coat; 80 h UV light) up to 1500 Hz there occurs an average decrease of accelerance of 2.6 dB.

Eigenfrequencies: The absolute values of eigenfrequencies and loss factors is given in Figure 7c, their relative changes in Figure 7d, showing only those data for corresponding eigenmodes of white and varnished violins in principle having the same mode shapes. As the mode shapes of the instrument are a combination of cross-grain stiffness (being highly influenced by the varnish) and along-grain stiffness (in most cases a negligible effect) it is assumed that the eigenfrequency shifts caused by application to the instrument have values in between both effects. Indeed, this range of changes is measured which shows that the test-strip-results can be transferred to the instrument. As shown in 7d, the range of eigenfrequency shifts is between $\pm 6\%$ (which is $\pm$one semitone). Even the lower corpus resonances (A_0, C_2, T_1, B_1) are clearly shifted in eigenfrequencies. The values (in addition with those of another violin and a cello) are given in Table 2.

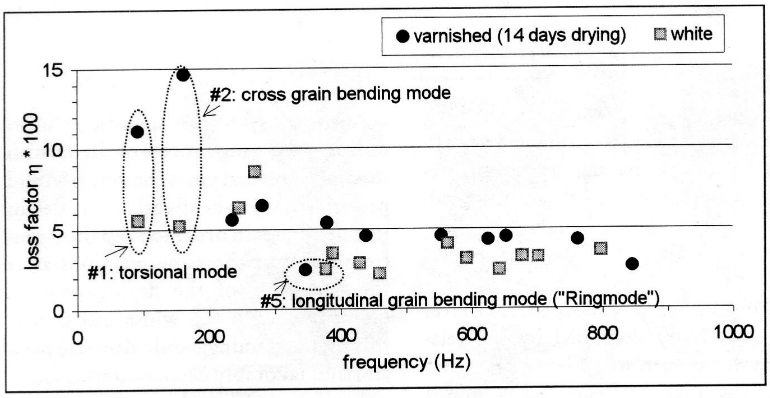
Accordingly to the acoustic changes during the drying process of the varnish used, after several years the violin would probably have to be slightly decreased in its thicknesses in order to keep the eigenfrequencies at the same positions as at the beginning of the drying process. Compared with the white instrument this slight thinning would decrease mass and thus favorably decrease impedance.

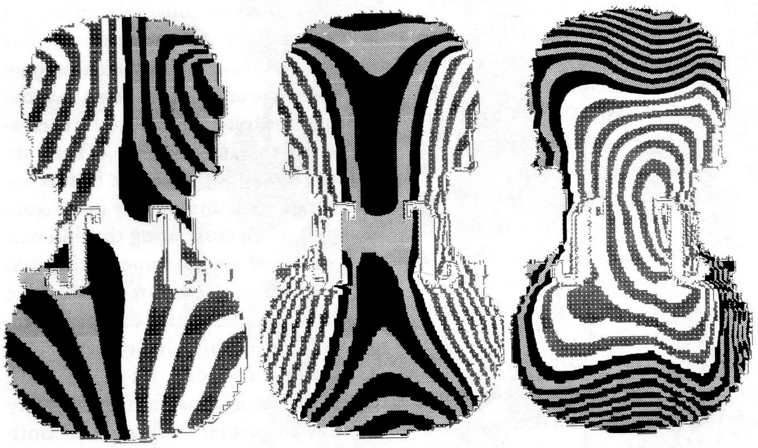
Loss factors: With changes up to 75 per cent the varnish considerably influences loss factors of the white instrument. For the loss factors, as for the eigenfrequencies, the range of changes shows that the results of the test-strip-method are transferable to the instrument. There are various reasons why the loss factors are not changed in a unique way (see Figure 7c and d) when comparing the different eigenmodes of the instrument with each other. In general, there are at least three reasons for differently damped resonance of the FRF of an instrument:

1) internal friction: As shown with the test-strips, internal friction is highly sensitive to primer and varnish. Both can be applied in a different way at different locations.

2) mode shape and anisotropy of internal friction: As internal friction is 3 to 4 times higher cross-grain than along-grain, the damping of each eigenmode depends on how much of its energy is saved in cross-grain bending and how much in along-grain bending. If a mode shape is modified by the varnish (because of the different stiffening cross-grain and along-grain)—which particularly happens at higher modes—, the above-mentioned ratio of cross- and along-grain bending and thus loss factor can change.

Figure 9a ▪ Comparison of white and varnished free violin top-plate: loss factors η (absolute values) above eigenfrequencies by curve-fitting frequency response functions (modal analysis). Note that comparing *eigenfrequency shifts is not possible* as thickness of top-plate had been reduced on the assembled instrument before varnishing (after white free top plate had been measured).
Figure 9b ▪ Mode shapes of torsional-mode #1 (left); cross-grain-bending-mode #2 (middle) and longitudinal-grain-bending-mode #5 (right) of free violin top-plate.





3) mode shape and radiation: Besides internal friction a second reason for the different peak widths in the FRF of a violin is the difference in radiation damping. If a mode shape, and thus radiation, is modified by the varnish, with a change of radiation efficiency there will be a change in loss factor as well. Concerning loss factor, the effect of varnish can be misinterpreted without distinguishing the above-mentioned reasons.

Besides these real reasons one must be aware not to confuse two modes with each other or to take two modes that are very close in frequency for one. If only a single FRF is measured and no mode shape information is obtained, both mistakes can happen easily because of the considerable frequency shifts. This is why a complete modal analysis of 125 FRF's had to be measured and calculated.

Changes of mode shapes: Modal analysis of the mode shapes (47 eigenmodes up to 2300 Hz) of the white and varnished violin show remarkable changes. Four examples of mode shapes are given in Figures 8a and b for the white and varnished violin. While up to mode #14 (white 731 Hz; varnished 748 Hz) the varnish caused nearly no mode shape changes at all (see mode T_1 and B_l), from #15 on (white 803 Hz, varnished 816 Hz) certain mode change modifications begin to occur (see #19) which increase with frequency (see *#25)*. At mode #21 for the first time there occurs a mode shape that does not have any similarity with any of white violin's (even with using the advanced curve fitting tool of the STAR Structure software which allows fitting and distinguishing modes having nearly the same frequency). While at low frequencies in most cases the same modes occur in both the white and varnished violin, from mode #35 on (1600 Hz) a unique classification is no longer possible. Obvious cross-grain stiffening leads to different mode-shape patterns at higher eigenmodes with decreasing sizes and increasing numbers of antinodes.

The free plates compared to the assembled instrument: Figure 9a shows the absolute values of changes of loss factor above the eigenfrequency of the free top plate for violin "Dan. 6,28" of Figures 7 and 8. (The shifts of eigenfrequencies cannot be compared, as the thickness graduation of the violin was modified from the outside after measuring the white free top plate and before varnishing the instrument.) It shows that for some modes the loss factor changes of the free plate are far higher (#1: +99%; #2: +281%) than on the assembled instrument, but for other modes (such as *#5:* +2.5%) there is no increase in loss factor. With respect to the mode shapes belonging to those modes (Figure 9b shows lines of the same amplitude), it appears that conclusions about grain orientation effects of the test-strips can be transferred to the violin's plate: precisely for that mode saving most of its energy in cross-grain bending (#2) the loss factor increases most, while that mode saving most of its energy in along-grain bending *(#5)* does not increase worth mentioning. The effect on the torsional mode (#1) is in between both.

Conclusions

The strip method is an easy method to predict the influence of primer and varnish on the acoustical properties of an instrument. This method can be applied by the violin maker even without any measurement equipment except a good pair of ears. Treating a strip, letting it dry, holding it at its nodal lines, tapping it with a finger, listening to the tone (its frequency and how long it rings) and comparing it with the tone of a reference strip can lead to some usable ideas about influence of the treatment. The violin maker might have a wide range of different primers and varnishes of different kinds and with them a creative palette of various tonal effects at his disposal. It is the author's hope that this work has helped to illustrate something about this palette. If the violin maker is convinced about his varnish and keeps it a secret, the trade "secret" will not be the varnish itself but the way it forms an acoustical unit with the instrument in the white. The art of varnishing is the ability to form the instrument in a way that takes into consideration the primer and the recipe used. The "secret" is knowing how to choose a suitable varnish that will be appropriate for the desired tonal pattern and then to treat the instrument in the suitable way. It is not the "palette" but is the picture that is painted. The statement that the Hill brothers (1963) make seems to be justified: "Fine varnish will not compensate for bad material or faulty construction; but that it makes or mars the perfectly formed instrument is, in our opinion, beyond dispute." ■ CASJ

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Appendix A

The author's test-strip-method is subject to uncertainties resulting from:

- Climate changes: The author did not have the opportunity of treating and measuring the strip samples in a climate controlled chamber—they were treated under normal workshop conditions. As all samples were being affected by the same climate during investigation time, relative comparisons are reliable.

  Absolute results were only possible by corrections obtained from untreated reference strips, a strategy which was also used by Schelleng (1968). To increase accuracy, the author used measurements on 20 reference strips, showing that velocity of sound stayed very constant within the drying period under different climate conditions while the loss factor, particularly cross-grain, did not. A general decrease of the cross-grain loss factor might have been caused by the further drying of the wood. The correction factors for a drying period of 4 and 9 years for velocity of sound and loss factor η are given in Table 3, columns 8 to 11. They were taken into account in all diagrams, except Figure 6. As the nine years performance of all reference strips is relatively unique one can assume a systematic (not arbitrary) measurement fault with the varnish-strip-method caused by the climate influence.
- Inconsistency in the application. In order to minimize this uncertainty two strips at a time were used for the same treatment. See commentaries under "Method: Test Environment and Measurement Uncertainties" above and Table 3, columns 4 to 7. The estimated maximum measurement fault as given in Figures 2 and 5 by rectangular error areas proceeds from the average values of these strips.
- Measuring method: A comparison of the applied method (using Impact hammer, FFT, Curve-fitting) shows good agreement with another method (using a sine-wave-driven coil above a little magnet (0.03g) that is fixed on the test strip).

Appendix B

Recipes of applied preparations and varnishes:

I. Alcohol—Varnishes

I.A.1.

Primer: "glue"

bone glue	10g
alum	1g

soak in water; heat; and paint in a dilution.

Varnish: "Alcohol Mittenwald"

shellac	10g
colophony	lg
copal (Manila)	lg
mastic	4g
propolis	3g
Venetian turpentine	2.5g
dissolve in alcohol	75ml

warm up; filter:

Source: Geigenbauschule Mittenwald. Fürst, A.

Table 3: Measurement uncertainties caused by measurement-method, climate changes and application differences of varnish. Resulting Correction-Factors for "Speed of Sound" c and loss factor η

Column	1	2	3	4	5	6	7	8	9	10	11
Type of strip	FFT-Coher	c error max	η error max	$\Delta c_1/\Delta c_2$ 4 year avg	$\Delta\eta_1/\Delta\eta_2$ 4 year avg	$\Delta c_1/\Delta c_2$ 9 year avg	$\Delta\eta_1/\Delta\eta_2$ 9 year avg	c_{corr} 4 year	η_{corr} 4 year	c_{corr} 4 year	η_{corr} 4 year
3mm along-grain	>.99	±1%	±10%	.73	.78	.71	.76	1.004	0.964	0.996	0.96
2mm along-grain	>.95	±1%	±10%	.78	.76	.77	.67	1.004	0.964	0.996	0.96
3mm cross-grain	>.97	±2%	±20%	.73	.82	.89	.76	0.98	1.07	0.960	1.49
2mm cross-grain	>.92	±2%	±20%	.95	.66	.90	.55	0.99	1.03	0.960	1.55

Explanations:
Column 1: FFT-Coher: minimum value of the FFT coherence-function within the 3 dB Bandwidth of the eigenfrequency (4 Averages)
Columns 2 and 3: c error max. and η error max. are maximum estimated errors of average values. See error areas in diagrams.
Columns 4 through 7: $\Delta c_1/\Delta c_2$ and $\Delta\eta_1/\Delta\eta_2$ show the average ratios of respectively two strips (index 1 and 2) of the same type with same treatments ("twins"), which means that the columns show the natural application differences of primer and varnish caused by differences in absorption, brush-technique, etc.

$\Delta c_1 = c_1 - c_0$; where c_0 = velocity of sound c of untreated strip; $c_1 = c$ of varnished strip.
$\Delta\eta_1 = \eta_1 - \eta_0$, where η_0 = lossfactor η of untreated strip; η_1 = loss factor η of varnished strip
4y and 9y are values 4 and 9 years after application of varnish.

Note: Comparing $\Delta c_1/\Delta c_2$ 4 year avg with $\Delta c_1/\Delta c_2$ 9 year avg and $\Delta\eta_1/\Delta\eta_2$ 4 year avg with $\Delta\eta_1/\Delta\eta_2$ 9 year avg indicates that most of the uncertainty is caused by differences in the application of varnish on the strip rather than by measurement-uncertainty or climate-changes.
Note: Values of $\Delta c_1/\Delta c_2$ (.73 and .71) are not very meaningful for along-grain strips. Changes in c are very small; hence, the ratios $\Delta c_1/\Delta c_2$ are the quotients of two very small numbers, both approximately zero.
Columns 8 through 11: c_{corr} and η_{corr} These are correction factors for respective strip types which result from observing value-changes of twenty different *un*treated reference-strips. These correction factors are taken into account in all the diagrams except Figure 6.

Example for a strip with along-grain grain orientation and 3 mm thickness:
$\eta_{untreated} = \eta_0 = 0.52 * 10^{-2}$. After 9 years $\eta = 0.50 * 10^{-2}$.
Correction factor η_{corr} 9 year = 0.50/ 0.52 = 0.96 (Values of Table 1 are given as average-values of all the reference-strips of the same type.)
Measurement of Varnish-application:
Specimen before treatment: $\eta_{untreated} = 0.54 * 10^{-2}$
Same strip treated anno 1988 and measured anno 1997: $\eta_{treated} = 0.61 * 10^{-2}$
Correction with calculated correction-factor: $\eta_{treated\,corrected} = 0.61 * 10^{-2} * 0.96 = 0.586$
Final result as shown in the diagrams
$\Delta\eta / \eta_0 = (\eta_{treated\,corrected} - \eta_0) / \eta_0 = (0.586 - 0.52)/0.52 = 0.127$
Interpretation: This varnish treatment has caused a (corrected) increase of the loss-factor η of the along-grain-grain spruce strip with a thickness of 3 mm by a factor of 1 + 0.127 = 1.127 or + 12.7%.

I.B.1.
Primer: "Aracelian"
gum resin Myrrh 10g
copaiva—balsam 3g
dissolve in alcohol 20ml

2. *Varnish:* "Aracelian"
Myrrh 20 g
spike oil 5 g
sandarac 2 g
copaiva—balsam 6 g
dissolve in alcohol 55 ml

Source: Aracelian. S. 1965. "Mon vernis a base de Myrrhe." (Teheran)

I.C.1.
Primer: "casein"
latic fermentation 10 g
soak in water 55ml
heat: 1 h at 60° C
natron lixivinum 25% 2 ml
heat: 1 h at 95° C
cool down:
spike oil 15 ml
Source: Dörner. M. 1985. *Malmittel und seine Verwendung im Bilde.* (Stuttgart) p. 75.

Varnish; "Retouchierlack"
ready—made varnish by a varnish ingredient dealer
Source: Pa. Hammerl. Baiersdorf

II. Essential Oil Varnishes
II.A.1.
Primer: "Bonnani"
sandarac 5 g
dissolve in warm oil of lavender 9 ml
Source: according to a recipe by the Jesuitpadre Bonnani. (Roma 1713) in: Mailand, E. 1903. "Das wiederentdeckte Geheimnis des altitalienischen Geigenlackes", (Leipzig), p.14]

Varnish: "Essential Mittenwald"
mastic 16 g
dammar 8 g
melted copal 8 g
dissolve in oxidized turpentine oil 150 ml
then linseed oil 10 g
siccative 5 ml
left to stand for a few years
Source: see I.A.

II.B.1.
Primer: "Sacconi"
a) waterglass (Na) (2 treatments)
b) "white varnish" (1 treatment):
arabicum gum 17g
honey 1/2 teaspoon
sugar 1/4 teaspoon
heat and filter: after cooled down mix with precipitated part of one whisked egg

Varnish "Sacconi"
Venetian turpentine 30 ml
heat up in an iron pan together with lime
propolis 30 g
alcohol 30 ml
heat until it becomes a pulp
then dilute in spike oil
Source: Sacconi, S. F. "Die 'Geheimnisse' Stradivaris". Frankfurt/M. 1981, p.171.

III. Fatty Oil Varnishes
III.A.1.
Primer: "walnut oil"
warm wal nut oil

Varnish: "Zanetto"
colophony 10 g
Venetian turpentine 10 g
dissolve in 1.5 % concentrated nitric acid
heat until it becomes a pulp
oxidized walnut oil 75 ml
burned pulverized lime
cook resins in the oil
Source: Baese. G. 1987. "Classic Italian Violin Varnish" *Journal of the Violin Society of America.*

III.B.1.
Primer: "linseed oil
cold pressed "oxidized" linseed oil
cook bone glue in water and mix with the warm oil

a *Varnish*: "linseed oil/mastic
"oxidized" linseed oil 30 g (cold pressed)
mastic 15 g
Venetian turpentine 15 g
cook resins in the oil; give certain amount of oil to it in the end

b *Varnish*: "linseed oil/ amber"
"oxidized" linseed oil 30 g
amber 12 g
cook amber in the oil
Source: see III.A.