The Effect of Finishes on the Vibration Properties of Spruce Guitar Soundboard Wood

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Abstract -This paper presents a study of the effect of a sealer and four finishes on the vibration properties of spruce for guitar soundboards. Two of the finishes, de-waxed shellac and nitrocellulose instrument lacquer, are evaporative finishes, traditionally used for guitars. The third and fourth are reactive shellac-based finishes. The study measured the fundamental vibrational frequency, f_0, and damping quality factor, Q, of Sitka spruce test bars machined in along-grain and cross-grain orientations, and coated with sealer and the finishes. The sealer alone produced significant changes in both f_0 and Q for the two grain orientations: the along-grain f_0 decreased; the cross-grain f_0 increased, and Q for both grain orientations decreased. The finish top coats affected f_0 for only the along-grain bars, which decreased with top coat application. Compared to Q for the sealer coating, all of the top coats cured for seven weeks increased Q for the along-grain bars, but did not affect Q for the cross-grain bars. Statistical analyses showed that all of the top coat finishes cured for seven weeks were equivalent with respect to their effect on the vibrational properties of the spruce bars.

I. Introduction

Finishes serve to protect and enhance the beauty of musical instruments. Also, it is well-known that finishes can modify the acoustics of an instrument. This study reports the results of tests of the effect of a sealer and four top coat finishes on the vibration properties of spruce guitar soundboard wood. Two of the top coat finishes, de-waxed shellac and nitrocellulose instrument lacquer, are evaporative finishes. The third and fourth are reactive shellac-based finishes, that after evaporation of the solvent, continue to cure by chemically cross-linking to form top coats that are more durable than evaporative finishes.

Many of the physical and chemical characteristics of evaporative and reactive finishes are different [1]. This presents an important question for the luthier: do they also affect the vibration properties of the wood differently? The purpose of this study is to compare the vibration properties of spruce soundboard wood finished with sealer, followed by top coats of two evaporative finishes (dewaxed shellac and nitrocellulose instrument lacquer), and two reactive modified shellac-based finishes.

Two methods were used to examine the vibration properties of the bare wood, and the wood with sealer and finishes:

1) Measurement of the fundamental vibrational frequency, f_0 (resonant frequency), of wood sample strips (thin bars) with free ends; and
2) Measurement of the damping quality factor, Q, at the fundamental resonant frequency by the logarithmic decrement method.

A significant part of this investigation was the measurement and control of sample-to-sample variation of finish thickness. Previous studies of the impact of finishes (primarily varnish) on f_0 and Q (or the logarithmic decrement) had noted the consequences of variation in finish thickness for interpreting measurement results, but had not reported finish thickness nor variation in thickness for the samples of the measurements.

Schelleng [2] discussed how varnish thickness affects the vibrational properties of wood, noting "…deviations occur depending on manner of application…" and "… thickness did not differ radically from sample to sample." Schleske [3], in his study of violin varnish, concluded that "…most of the uncertainty [in the properties measured] is caused by differences in the consistency of application rather than by measurement uncertainties…"

A focus of this study was to limit measurement errors due to the variability of finish thickness, and to quantify the precision of measurement of finish thickness, and the vibration properties f_0 and Q so that statistical analyses could

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be used to evaluate the results. This study included the control and measurement of sample-to-sample variation of areal density and thickness, a component not included in previous studies.

Details of the measurements and results are presented in the following sections of this paper.

II. Experimental

A. Materials

Test Bars Sitka Spruce (Picea sitchensis), a popular wood for guitar soundboards, and widely available in high quality panels, was chosen for the test bars. To diminish the effects of bar-to-bar variation on the results of the vibration tests, care was taken to select high quality spruce and to machine the bars to uniform dimensions. A pair of book matched AAA grade panels was obtained from Luthiers Mercantile International, Inc.[2] One panel (labeled 3A) of the pair was used for all of the test sample bars. The other panel (3B) was reserved for future plate mode studies. The panels were well quarter sawn, with little, if any, observable cross-grain run out. The growth ring spacing ranged from about 1.0 to 1.5 mm and the growth ring pattern was uniform across the panel. Upon receipt, the wood was equilibrated with shop humidity and temperature, maintained at 66° to 76° F and 35% to 40% relative humidity. As received, panel dimensions were 55 cm long by 22 cm wide by 3.8 mm thick.

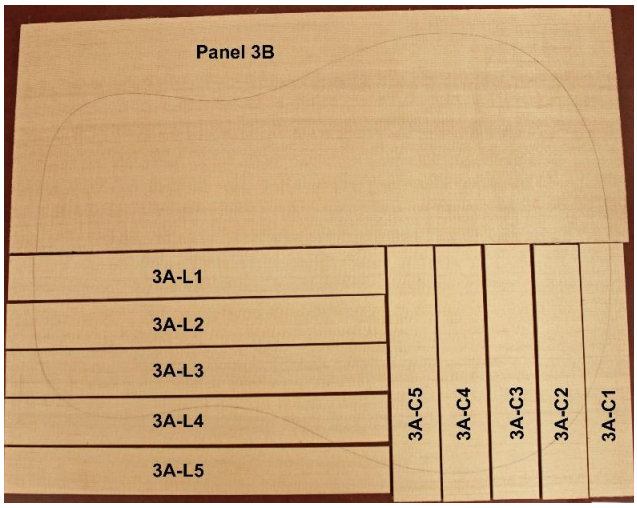

Photo 1 – Location of test bars cut from one of the book matched panels. The panel at the top of the photo is 3B. The test bars were cut from book matched panel 3A at the bottom. Labels give the test bar identification numbers. L1 through L5 refer to along-grain bars 1 through 5. C1 through C5 refer to cross-grain bars 1 through 5. Note: a faint pencil outline of a guitar top, drawn by the supplier, can be seen on the panels.

After the panel edges were trimmed to ensure alignment of the wood grain with the long edge, ten bars were machined from the 3A spruce panel. Five of the bars were machined with the grain running parallel to the long edge (the along-grain bars). Another five of the bars were machined with the grain perpendicular to the long edge (the cross-grain bars). The location of each bar cut from the panel was documented photographically (see Photo 1). The two sets of five bars were stacked and trimmed together to ensure the lengths and widths within each set were the same.

Following careful sizing of the length and width of the bars, they were sanded with a *Luthier's Friend*[3] sander with a 120 grit drum, to a thickness of 3 mm (which is within the thickness range of 2.7 to 3.2 mm for a large body steel string guitar) [4]. This was followed by sanding, using a block, with 220, then 320 grit paper.

After sanding, bar dimensions and weights were measured, and the densities were calculated. Lengths and widths were measured to the nearest 0.01 cm using a precise ruler, and digital calipers. Thicknesses were measured with a micrometer graduated to 0.001 inch. The bars were weighed with a digital scale precise to 0.1 gram. Length and thickness were sized to produce an approximate fundamental frequency that was above the lower range (approximately 60 Hz) of the sine wave sound generating equipment. The target for the cross-grain bars was ~100 Hz. The target was ~170 Hz for the along-grain bars.

	Along-grain bars			Cross-grain bars	
	Average	Std. Dev.		Average	Std. Dev.
Length (cm)	33.39	0.01		21.84	0.02
Width (cm)	4.01	0.01		4.01	0.01
Thickness (cm)	0.308	0.003		0.299	0.009
Weight (g)	18.8	0.3		12.02	0.1
Density (g/cm^3)	0.456	0.004		0.459	0.003

Table 1 – Averages and standard deviations for dimensions, weights and densities of the two sets of the unfinished test bars.

Table 1 gives the average and standard deviation of the dimensions, weights and densities of the bars prior to application of the finish. As can be seen from Table 1, the dimensions and weights of the bars within both the along-grain and cross-grain sets were uniform, as were the densities of all the bars.

[2] Luthiers Mercantile International, Inc., 7975 Cameron Drive, Bldg. 1600, Windsor, CA 95492http://www.lmii.com/
[3] Ken Picou Design, 5508 Montview, Austin, TX 78756

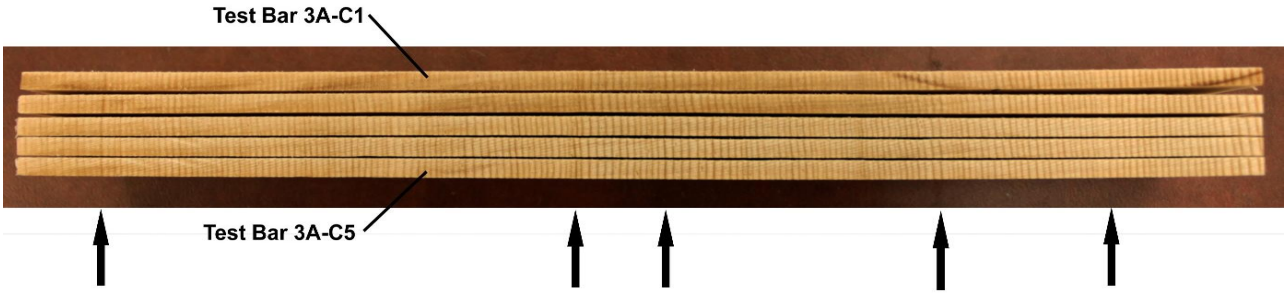

Photo 2 ─ Edge-on view of the cross-grain bars stacked to show alignment of the annual growth ring pattern. The top bar is labeled 3A-C1, and the bottom 3A-C5. The arrows point to distinctive annual growth ring pattern features that are the same for all the bars.

Uniformity of the annual growth ring (grain) pattern of the cross-grain bars is shown in Photo 2, an edge-on view of the stack of the five cross-grain bars. Alignment of identical features of the grain of each bar demonstrates that the bars were well matched. From Photo 2 it is also seen that panel 3A was well quarter sawn: the annual growth rings, from one end of each bar to the other end, were all perpendicular to the surface of the bar.

Finishes One sealer with four different top coat finishes were used for this study:

1) Sealer: *Seal-Lac*,[4] comprised of dewaxed super blonde shellac and natural resin additives (comparable to a 2 lb cut[5] of shellac);
2) Dewaxed shellac: dewaxed super blonde shellac flakes[4] dissolved in anhydrous 200 proof denatured alcohol to form a 2 lb cut;
3) Modified dewaxed garnet shellac: *Royal-Lac Garnet*[4], formulated from dewaxed garnet shellac dissolved in anhydrous 200 proof denatured alcohol and modified with synthetic and natural resins to form a reactive finish;
4) Guitar lacquer aerosol: *ColorTone* Clear Gloss No. 3881 Nitrocellulose Lacquer[6], in an aerosol spray can;
5) Modified dewaxed shellac aerosol: *Royal-Lac Clear Coat*[4], formulated from dewaxed super blond shellac dissolved in anhydrous 200 proof denatured alcohol and modified with synthetic and natural resins to form a reactive finish, and provided in an aerosol spray can.

For this finish study, the test bars were paired into five sets of two bars, each set consisting of one along-grain and one cross-grain bar. The sets received the top coat finish treatments shown in Table 2.

Test bars 3A-L3 and 3A-C3 were left unfinished (bare wood) to serve as controls during the course of vibration measurements. Measurements made on these control test bars aided in determining the repeatability and precision of the results.

SET No.	ALONG-GRAIN BAR	CROSS-GRAIN BAR	TOP COAT FINISH TREATMENT
1	3A-L1	3A-C1	Dewaxed Shellac
2	3A-L2	3A-C2	Modified Dewaxed Garnet Shellac
3	3A-L3	3A-C3	No Finish - Control Test Bar Set
4	3A-L4	3A-C4	Guitar Lacquer Aerosol
5	3A-L5	3A-C5	Modified Dewaxed Shellac Aerosol

Table 2 ─ Top coat finishes for the test bar sets.

B. Procedure

Application of Finishes Because of the small size of the test bars, spraying was found to be the most effective way to evenly apply the sealer coats, and all of the finish top coats. A Preval portable sprayer[7] was used to apply the sealer, dewaxed shellac, and the modified dewaxed garnet shellac. The guitar lacquer aerosol and modified dewaxed shellac aerosol were applied using the aerosol spray cans.

Determination of Finish Thickness Because finish thickness affects the resonant frequency and damping of the test bars, comparison of the effect of finishes on these vibration properties calls for a uniform thickness of finish film

[4] ShellacFinishes, 7740 Goldfish Way, San Diego, Ca 92129;http://www.shellacfinishes.com
[5] Dry shellac is mixed with denatured alcohol in a particular ratio called a cut, which refers to the amount of shellac in pounds dissolved in a gallon of alcohol. A 2-lb. cut of shellac is 2 lb. of shellac resin dissolved in a gallon of alcohol.
[6] Stewart-MacDonald, 21 N. Shafer Street, Box 900, Athens, OH 45701,http://www.stewmac.com
[7] Chicago Aerosol, 1300 E. North St., Coal City, IL 60416

on each bar, and bar-to-bar uniformity of thickness. Film thickness and uniformity are controlled by application technique, monitored by determination of film thickness.

Direct measurement of the thickness of films on the order of a hundred microns, μ (1μ = 10^{-6} m) requires special measurement tools. For wood substrates, a dry film ultrasonic thickness gage, not available for this study, can be used. However, disadvantages of the ultrasonic gage are the inability to distinguish film layers of similar density, and the use of a gel to couple the probe to the surface of the film. The gel can contaminate the surface of the film, interfering with adhesion of subsequent coats of sealer or finish.

An alternative to direct film thickness measurement, average areal density, was used in this study to evaluate and monitor film thickness. Average areal density is determined by weighing a bar to measure film mass, then dividing the mass by the area of the surface of the bar. Average film thickness is calculated by dividing the average areal density by a reported value of the dry film volumetric density. To avoid confusion with the term average, meaning arithmetic average, in the following sections of this article the terms *areal density* and *thickness* are used to denote *average areal density* and *average thickness* as defined above.

Measurement of the areal density to evaluate finish thickness requires only precise rulers, calipers, micrometers, and a weighing scale. However, it is an average value of thickness that is determined; uniformity of film thickness on a particular bar is not evaluated. Undetected variations in the uniformity of finish thickness on a bar will contribute to imprecision in the measured values of the vibrational properties of the coated bars. Accordingly, careful attention was paid to finish application technique (use of spray application, proper thinning, building of thickness with light coats, level sanding between coats, and final level sanding) to reduce film thickness variations. Also, significant effort was spent to evaluate the bar-to-bar precision of the areal density and thickness of the sealer and top coat finishes.

There are several sources that report useful information to serve as a guide for the appropriate amount of finish on instruments, and hence the amount for the test bars used in this study:

1) Michelman [5], in his study to recreate violin varnishes of the old Italian Masters, reported using a “thinness” of combined sub-varnish (i.e. sealer) and varnish coats ranging from 0.0040 inch (101 μ) to 0.0052 inch (132 μ), with a sub-varnish “thinness” of 0.0015 inch (38 μ).

2) Data reported by Schelleng [6] indicates that he used coatings of 0.013 g/cm^2, about 0.005 inch (127 μ), on his test bars for vibration property studies.

3) According to Gore and Gilet [7], for their guitar finishes: “We frequently use shellac (French Polish) as the base for our nitrocellulose finishes on soundboards and keep the total finish thickness on tops very low, never more than 100 microns”.

4) In a YouTube video[8] of a tour of the Taylor Guitars factory in El Cajon, CA, the Taylor Guitars guide and narrator stated that it is important to “keep the finish absolutely as thin as you possibly can.” He indicated that the thickness of the Taylor uv-cured polyester finish is 0.006 inch (152 μ) for most of their guitars. For the Taylor 800 series guitars he indicated the finish thickness was 3½ mils (89 μ).

Using this information, it was decided to keep the combined sealer and top coat thickness to less than 100 μ (0.004 inch). This thickness is within the norm of lutherie practice, as discussed above.

The areal density ρ_a (mg/cm^2) of the film was used to monitor the amount of finish on the surface. Thickness, T, can be calculated from the areal density and reported values of the volume density, ρ_v (g/cm^3), or specific gravity of the coating materials:

$$T = \rho_a / \rho_v \quad (1)$$

The mass of the coatings (m_c) was determined, by weighing the test bars with a digital scale, as the difference between the mass before (m_1) and after (m_2) a step of the finish process:

[8] https://www.youtube.com/watch?v=08vFIhdfXIk, segment time—32:30 to 33:40 minutes, R. Christopher, May 12, 2014.

$$m_c = m_2 - m_1 \quad (2)$$

Coating areal density ρ_a is determined from the calculated mass of the coating m_c divided by the surface area A of the coating:

$$\rho_a = m_c / A \quad (3)$$

The surface areas of the coatings were calculated from the average length, width and thickness of the bars, given in Table 1. The area of the edges of the bars (less than 10% of the total area) were included where noted in the following sections.

Bar-to-bar uniformity of coatings, areal densities and thicknesses of the test bars was achieved by calculating, prior to final level-sanding, the mass m_c for the desired coating areal density. During final level-sanding, the bars were weighed frequently to monitor the approach to this mass. Final coating areal density and thickness were calculated as noted in equations (3) and (1).

Measurement Precision and Confidence Intervals Comparison of coating amounts to judge the similarity of values, requires an estimate of the precision of the areal densities and thicknesses. For this study, the resolution, or least count of the digital scale, 0.1 g, limits the precision for determination of areal density and thickness. The reading error, 0.05 g, equal to half of the least count, can be taken as an estimate of the standard deviation of the masses of the sample bars.

The areal densities and thicknesses were derived from the difference of two masses, each with a standard deviation of 0.05 g. From the formula for compounding subtraction errors, the estimate of the standard deviation of the mass of the coatings, s_m, is $\sqrt{2}$ (0.05 g), or ± 0.07 g. This estimate of s_m is used as the basis for calculation of the margin of error which reflects the amount of random measurement error.

For the coating areal density, the margin of error, ξ_A is:

$$\xi_A = k\,(s_m/\sqrt{n})/A \quad (4)$$

where k is the two-tailed Student t-statistic for the chosen level of significance for sample size n. For the thickness, the margin of error is:

$$\xi_T = \xi_A / \rho_v \quad (5)$$

A confidence interval[9] about a population mean for the areal density ρ_p, is constructed from the margin of error and the mean of the areal density measurements for the coatings (the sample mean), ρ_s:

$$\rho_s - \xi_A \le \rho_p \le \rho_s + \xi_A \quad (6)$$

As an example of calculating the margin of error and confidence interval for the areal density, consider the data in Table 3 for the along-grain test bars with sealer applied to both sides. The surface area (both sides and edges) is 290 cm^2. (The edge surface area was included because over-spray also coated the edges and contributed to the weight of the sealer.) The areal densities were calculated using equation (3). The estimate of the standard deviation for the areal density of the coatings, s_m/A is 0.3 mg/cm^2. The sample size n (number of bars) is 4 and the sample mean for the areal densities from Table 3 is 5.3 mg/cm^2. At a level of significance of 0.05 (95% confidence level), the two-tailed Student t-statistic, k, is 3.18. (Note that use of the Student t-distribution for estimating confidence intervals was designed to treat small sample sizes, typically less than 15.)

The margin of error, according to equation (4), is 0.5 mg/cm^2, yielding a 95% confidence interval for the population mean of the areal densities, ρ_p, of $4.8 \le \rho_p \le 5.8$. As all of the areal densities measured for the along-grain samples fall within this confidence interval, the values can be considered equivalent, with differences due to random measurement error.

Because the same finish procedure was used for all of the bars, the bar-to-bar margin of error can also be used as an estimate of the uniformity of finish coating areal density and thickness for a single bar.

[9] For a discussion of this method of constructing a confidence interval see Wilson [8].

Sealer Application Sealer was applied with the Preval portable sprayer. Six coats, two coats per day, were applied to each side of the test bars. The first two coats used a 2 lb cut and the remainder a 1.5 lb cut. A drying time of one to four days was allowed between each set of two coats. The bars were level-sanded after drying with a sequence of 220, 320 and 400 grit paper. Final level-sanding was performed with the sequence of 220, 320 and 400 grit paper, followed by Micro-Mesh™ 1800.[10] The bars were weighed and the amount of finish (areal density and thickness) was calculated using equations (1), (2), and (3).

Table 3 presents the masses of the sealer coatings applied to both sides, and the calculated areal densities and thicknesses. Thicknesses of the sealer coatings were calculated from the areal densities and a value of 1.1 for the specific gravity of shellac, taken from a published range of values[11] (1.02 to 1.12). The area, A, for calculation of the areal density of the bars included the surface of both sides (equal to 268 cm^2 for the along-grain bars; 175 cm^2 for the cross-grain bars), and the edges (equal to 22 cm^2 for the along-grain bars; 16 cm^2 for the cross-grain bars). It can be seen from the confidence intervals in the caption for Table 3 that the areal densities and thicknesses of the coatings of the bars within each set were equivalent.

TEST BAR NUMBER	MASS WITH SEALER ON BOTH SIDES (g)	AREAL DENSITY OF SEALER (EACH SIDE) (mg/cm^2)	THICKNESS OF SEALER (EACH SIDE) (μ (10^{-6} m))
ALONG-GRAIN			
3A-L1	1.6	5.5	50
3A-L2	1.6	5.5	50
3A-L4	1.6	5.5	50
3A-L5	1.4	4.8	44
	MEAN =	5.3	49
MARGIN	OF ERROR, ξ =	0.5	5
CROSS-GRAIN			
3A-C1	1.0	5.2	48
3A-C2	1.0	5.2	48
3A-C4	1.0	5.2	48
3A-C5	1.0	5.2	48
	MEAN =	5.2	48
MARGIN	OF ERROR, ξ =	0.6	6

Table 3 – Sealer mass, areal density and thickness after application to both sides of the test bars. Confidence intervals for areal densities (mg/cm^2)--along-grain set: $4.8 \le \rho_p \le 5.8$; cross-grain set: $4.6 \le \rho_p \le 5.8$. Confidence intervals for thicknesses (in microns)--along-grain set: $44 \le T_p \le 54$; cross-grain set: $42 \le T_p \le 54$.

Measurement of the resonant frequency and damping of the bars, performed at this point in the study, showed a significant change in these properties. Because of this, it was decided to remove the sealer from one side of the bars to more nearly approximate the finish of a guitar top plate that usually has either a thin wash coat of sealer on the inside, or none at all.

Removal of the sealer was accomplished by sanding, using a progression of 180 to 220 grit paper to Micro-Mesh 1500. Progress of sealer removal was judged both visually and by weighing the bars frequently during sanding. The test bar side with the sealer coating remaining was designated as the top side, to be coated with the top coat finish, as listed in Table 2.

Table 4 presents the mass of the sealer coating applied to the top side of each bar, and the calculated areal density and thickness. From comparison of the sealer coating mass values for the bars in Table 3 to those in Table 4, it can be seen that half of the total mass of sealer was removed from the bars coated on both sides. This indicates that, within the margin of error for determining mass, half of the sealer was removed. However, any unmeasurable amount of sealer remaining, or undetected small amount of wood removed during the sanding process, would contribute to measurement imprecision of the vibrational properties.

TEST BAR NUMBER	MASS OF SEALER ON TOP SIDE (g)	AREAL DENSITY OF SEALER (mg/cm^2)	THICKNESS OF SEALER (μ (10^{-6} m))
ALONG-GRAIN			
3A-L1	0.8	5.1	47
3A-L2	0.8	5.1	47
3A-L4	0.8	5.1	47
3A-L5	0.7	4.5	41
	MEAN =	5.0	45
MARGIN	OF ERROR, ξ =	0.8	7
CROSS-GRAIN			
3A-C1	0.5	4.8	44
3A-C2	0.5	4.8	44
3A-C4	0.5	4.8	44
3A-C5	0.5	4.8	44
	MEAN =	4.8	44
MARGIN	OF ERROR, ξ =	1.1	10

Table 4 – Sealer mass, areal density and thickness applied to the top side of the test bars. Confidence intervals for areal densities (mg/cm^2)--along-grain set: $4.2 \le \rho_p \le 5.8$; cross-grain set: $3.7 \le \rho_p \le 5.9$. Confidence intervals for thicknesses (in microns)--along-grain set: $38 \le T_p \le 52$; cross-grain set: $34 \le T_p \le 54$.

The area, A, for calculation of the areal density of the bars coated on only the top side included the surface of the top (equal to 134 cm^2 for the along-grain bars; 88 cm^2 for the cross-grain bars), and the edges (22 cm^2 and 16 cm^2, respectively) as previously discussed. Because of the fixed weighing error of 0.07g, and a coated surface area about half of that of the test bars coated on both sides, the calculated margin of error values for the areal densities and thicknesses are larger.

[10] Micro-Surface Finishing Products Inc., 1217 West 3rd Street, PO Box 70, Wilton, Iowa 52778, http://micro-surface.com/
[11] Kremer Pigmente, Safety Data Sheet, March 1996, pg. 1

Again, within the margins of error, the areal densities and thicknesses of the sealer coatings of the test bars within a set were equivalent. Additionally, comparison of the means and margins of error for the areal densities and coating thicknesses given in Table 3, to those in Table 4, indicates that the coating thicknesses on each side of the bars, when originally coated, were equivalent.

Top Coat Application As with the sealer, finish top coats were applied by spraying. One pound cuts of dewaxed super blonde shellac and modified dewaxed garnet shellac were applied with the Preval sprayer. The guitar lacquer aerosol and modified dewaxed garnet shellac aerosol were applied according to the instructions on the aerosol cans.

Three coats a day were applied, for a total of nine coats. A drying time of one to two hours was allowed between coats applied within the same day. Then the bars were allowed to dry at least overnight before weighing and level-sanding. Final level-sanding was achieved by dry sanding with 320 grit, followed by Micro-Mesh 1500, 1800 and 2400. Prior to final level-sanding, the weight of the top coat to achieve the desired film areal density was calculated. During final level-sanding, the bars were weighed frequently to monitor the approach to this weight. Vibration property measurements were performed on the bars four days after the last top coat was applied, and again after the top coat finish had cured for seven weeks.

TEST BAR NUMBER	TOP COAT FINISH	MASS OF TOP COAT (g)	AREAL DENSITY OF TOP COAT (mg/cm^2)	THICKNESS OF TOP COAT μ (10^{-6} m)
ALONG-GRAIN				
3A-L1	DEWAXED SHELLAC	0.7	4.5	41
3A-L2	MODIFIED DEWAXED GARNET SHELLAC	0.7	4.5	41
3A-L4	GUITAR LACQUER AEROSOL	0.6	3.8	28
3A-L5	MODIFIED DEWAXED SHELLAC AEROSOL	0.8	5.1	47
		MEAN =	4.5	39
	MARGIN	OF ERROR, ξ =	0.8	7
CROSS-GRAIN				
3A-C1	DEWAXED SHELLAC	0.5	4.8	44
3A-C2	MODIFIED DEWAXED GARNET SHELLAC	0.4	3.8	35
3A-C4	GUTAR LACQUER AEROSOL	0.5	4.8	36
3A-C5	MODIFIED DEWAXED SHELLAC AEROSOL	0.5	4.8	44
		MEAN =	4.6	39
	MARGIN	OF ERROR, ξ =	1.1	10

Table 5 – Mass, areal density and thickness of top coat finishes for test bars. Confidence intervals for areal densities (mg/cm^2)--along-grain set: $3.7 \le \rho_p \le 5.3$; cross-grain set: $3.5 \le \rho_p \le 5.7$. Confidence intervals for thicknesses (in microns)--along-grain set: $32 \le T_p \le 46$; cross-grain set: $29 \le T_p \le 49$.

Table 5 presents the masses of the finish coatings applied to the top sides of the test bars, and the calculated areal densities and thicknesses. The area, A, for calculation of the areal density included the area of the top and the edges, as previously given. Thicknesses of the dewaxed shellac, modified dewaxed garnet shellac, and modified dewaxed shellac aerosol films were calculated from the previously given value of 1.1 for the specific gravity of shellac. A value of 1.35 for the dry film density of the nitrocellulose lacquer, determined from solids data for a lacquer formulation by Chemcraft,[12] was used to calculate the thickness of the nitro-cellulose lacquer top coat.

As with the sealer coatings, the areal densities of the top coats of all test bars in Table 5 were found to be equivalent within the margins of error. However the calculated thickness for the guitar lacquer fell just outside of the lower limit of the confidence interval for along-grain bar finish thickness by 4 μ. This was due to the higher value (1.35) for the volumetric density of lacquer, compared to shellac (1.1), used to convert values of areal density to thickness. No weight change was detected for any of the bars between the times of initial vibration measurements at four days after the top coat was applied, and after the seven weeks cure time.

Finish on Along-Grain Bars	Areal Density ± Margin of Error (mg/cm^2)	Thickness ± Margin of Error (microns)
Sealer (Top Side)	5.0 ± 0.8	45 ± 7
Top Coat Finish	4.5 ± 0.8	39 ± 7
Total	9.5 ± 1.1	84 ± 10
Finish on Cross-Grain Bars		
Sealer (Top Side)	4.8 ± 1.1	44 ± 10
Top Coat Finish	4.6 ± 1.1	39 ± 10
Total	9.4 ± 1.5	83 ± 14

Table 6 – Summary of means and margins of error for the areal densities and thicknesses of the sealer and top coats, and the sum of these, for the sample bars.

Table 6 provides a summary of the areal densities and thicknesses of the finish coatings on the test bars. These are presented as the means of the values from Tables 4 and 5, along with the margins of error ($\pm\xi_A$ or $\pm\xi_T$) calculated at the 95% confidence level. The total areal densities and thicknesses were calculated as the sum of

[12] Chemcraft data sheet for Chemseal Amber NC Clear Sealer 546-5005, February 2010, Akzo Nobel Coatings, Inc., 1431 Progress Ave., High Point, NC 27261.

the mean values for the sealer in Table 4 and mean values of the top coats in Table 5. The margins of error for the totals of the sealer and top coats were calculated from the compounding of error formula for the sum of two quantities.

As can be seen from Table 6 the thickness of the sealer is equivalent for the along-grain and cross-grain bar sets, as is the thickness of the top coats. The total thickness of the finish (sealer plus top coat) for the along-grain bars was determined to be 84 ± 10 μ and that for the cross-grain bars is 83 ± 14 μ. Thus the goal of bar-to-bar uniform coatings less than 100 μ was achieved.

C. Vibration Measurements and Calculations

The fundamental resonant frequency f_0 and the damping Q factor of the bars were determined using the measurement equipment shown in Photo 3. Fletcher and Rossing [9] provide a detailed description of the resonance of bars with free ends, and Gore and Gillet [10] present a thorough description of the measurement of Q by the logarithmic decrement method.

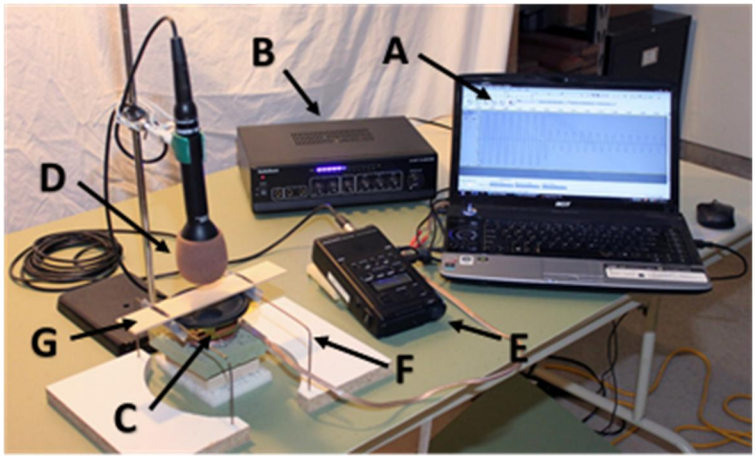

Photo 3 ─ Setup for measuring the vibration properties of the test bars. The components (A – G) are identified as follows: A) PC-based sine wave tone generator (NCH Software, Inc., http://www.nchsoftware.com/) and Audacity sound editing software (http://audacityteam.org/); B) 40-watt PA amplifier (RadioShack); C) Four inch audio speaker (Altec Lansing); D) Dynamic mic (Electro-Voice N/D367s); E) Digital audio recorder (Marantz PDM 660); F) Test bar support; and G) Test bar.

Fundamental Resonant Frequency The Chladni method [11-13] was used as the primary method to measure the frequencies of fundamental mode vibrations for the bars. Frequency spectrum analyses were used to check and verify the fundamental frequencies.

For the Chladni method, black glitter, obtained from a hobby shop, was sprinkled on a bar supported at its two vibrational nodes (positions of little vibration) by two narrow pieces of foam. For the fundamental frequency f_0, bar samples exhibit two nodes, at 22.4% of the bar length from either end. The audio speaker, driven by the amplified sine-wave signal, was positioned under the antinode (position of maximum vibration) at the center of the bar. The frequency was varied until the glitter started to vibrate, move, then settle on the vibrational nodes. The resonant frequency was indicated by the greatest vibration, as observed by the particle motion. With this method the frequency of maximum vibration (resonant frequency), can be measured within 1-2 Hz.

The resonant frequency measured by spectral analysis used the Audacity software Fast Fourier Transform (FFT) of the audio signal emanating from the vibrating bar during decay of the bar resonance (see the following damping section). Figure 1 shows the FFT frequency domain plot of the damping signal displayed in Figure 2 for bare wood along-grain bar 3A-L3. A Hann window, 44.1 kHz sample rate, and a sample size of 65536 were used to obtain the data in the Figure 1 plot. For determinations of f_0 using the FFT, sample sizes of 8192 or greater were used. Even spectrum peaks for lower resolution window sizes, used for the bars with lower Q values, agreed within one Hz with the Chladni measurements. For sample 3A-L3, the resonant frequency determined by both the Chladni method and spectral analysis was 172 Hz.

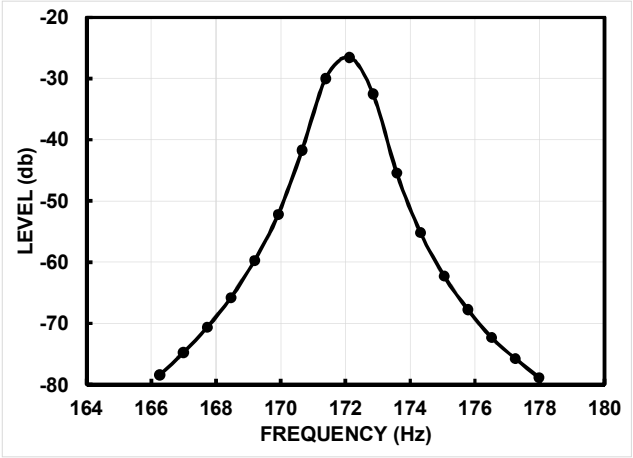

Figure 1 ─ FFT frequency domain plot of the damping signal displayed in Figure 2 for bare wood along-grain bar 3A-L3. FFT specifications: Hann window; 44.1 kHz sample rate; sample size = 65536.

The along-grain and cross-grain Young's moduli, E_L and E_C of the bare wood bars, were calculated from the measurement of f_0 for the along-grain and cross-grain bar samples [14]:

$$E = 10^{-9} (0.946 \rho \cdot f_0^2 \cdot L^4)/T^2 \quad (7)$$

Where E is Young's modulus (GPa), f_0 the resonant frequency (Hz), L the length (m), T, the thickness (m), and ρ the density (kg/m^3). Use of this equation assumes the bars are isotropic in the direction of bar length. While this assumption is valid for the spruce bars without finish, it is approximate for bars with finish on the surface, as the latter are composite structures. Therefore E_L and E_C were calculated for only the bare wood bars to confirm that the moduli for the spruce chosen for the tests were within accepted norms for guitar top plate wood.

Rearranging equation (7) shows the relationship [15] between f_0 and the unfinished bar parameters:

$$f_0 = 1.028 \, T/L^2 \, (E/\rho)^{1/2} \quad (8)$$

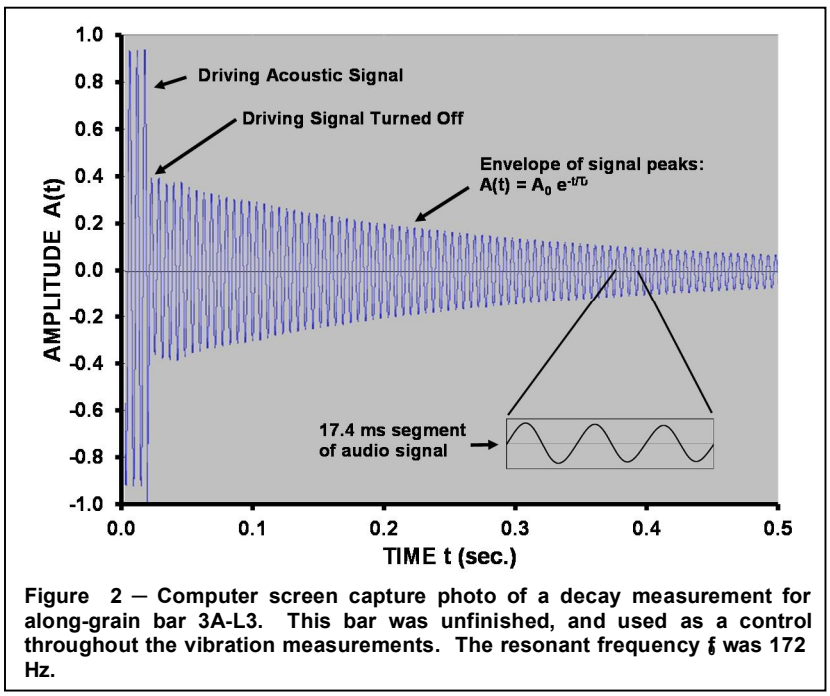

Figure 2 – Computer screen capture photo of a decay measurement for along-grain bar 3A-L3. This bar was unfinished, and used as a control throughout the vibration measurements. The resonant frequency f_0 was 172 Hz.

For the bars with a finish coating, the resonant frequency f_0, though only approximately represented by equation (8), is still an important measure of vibration properties, just as tap tones are for violin plates [16]. Within either an along-grain or cross-grain unfinished set of bars, the length, thickness and density were the same (see Table 1), and the finish thicknesses for a finish step were uniform (see Table 6). Thus a change in f_0 reflects a change in the bar stiffness and density resulting from the finish.

Damping Damping, often expressed as the quality factor, Q, was measured by the logarithmic decrement method at the resonant frequency of the bars. A detailed discussion of the measurement of Q is presented by Gore and Gilet [10].

To measure Q, a microphone was positioned above the bar (see Photo 3) to record the audio output at the resonant frequency. The bar, supported at its nodes, was set into vibration at the resonant frequency with a sinusoidal audio signal, the digital recorder was turned on, then the driving audio signal was turned off. After the driving audio signal was turned off, the microphone and digital recorder captured (recording format PCM-44.1 kHz) the decay of the amplitude of the resonant frequency audio signal emanating from the bar, as depicted in Figure 2. This audio signal was stored as a WAV (.wav) file to be analyzed by the Audacity sound editing program.

The audio signal stored in the WAV file was retrieved and displayed in the waveform view of the Audacity sound editing program. An example of this signal is shown by the blue trace in Figure 2.

The amplitude A(t) of the peaks of the decaying signal were measured as a function of the decay time, t. By expanding the amplitude and time scales, amplitude values could typically be read to ±0.002 unit and time to one millisecond.

Five to seven peak A(t) values, were taken from a portion of the decay curve. The decay rate equation,

$$A(t) = A_0 \, e^{-t/\tau} \quad (9)$$

where τ is the decay time constant, is linearized by taking the logarithm of both sides of the exponential equation, to yield:

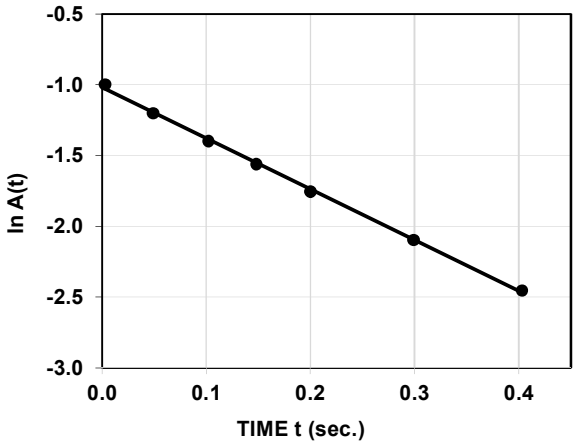

Figure 3 – Plot of ln A(t) vs. t for the decay curve shown in Figure 2.

$$\ln A(t) = \ln A_0 - t/\tau \quad (10)$$

Figure 3 shows a plot of ln A(t) vs. t for the decay curve shown in Figure 2. A linear least squares fit of the decay curve (ln(A), t) shown in Figure 2 was performed using the LINEST function of Microsoft Excel 2013. τ was determined from the slope of the line ($-1/\tau = -3.604\ \text{sec}^{-1}$) to be 0.277 sec. The standard error in τ, ± 0.015 sec, was calculated using the statistical functions for LINEST.

Q is calculated from f_0 and τ:

$$Q = \pi f_0 \tau \quad (11)$$

Damping is also often reported as the logarithmic decrement, δ:

$$\delta = 1/(f_0 \tau) = \pi/Q \quad (12)$$

For the example illustrated by Figures 2 and 3, Q is calculated from equation (11) to be 150 ± 2, and δ, from equation (12), to be 0.0209 ± 0.0006. In general the standard error of Q for data from a single measurement was less than ± 3 for all of the determinations of Q from the least squares fits.

III. Results and Discussion

A. Young's Moduli of Test Bars

The Young's moduli, E_L and E_C, were calculated for the along-grain and cross-grain unfinished (bare wood) test bars according to equation (7). Table 7 presents the results. The values are within the range of values determined by Hains [17] for Sitka spruce instrument wood. Note that while the values of E_C for all of the cross-grain bars are nearly equal, the values of E_L for the along-grain bars increase monotonically, from 15.7 GPa for bar 3A-L1 to 17.7 GPa, for bar 3A-L5 (an increase of 13%), in relation to the position on panel 3A (see Photo 1) from which the bar was cut. This variation of E_L for the along-grain bars is attributed to variation of the wood microstructure across the plate. The parity of E_C for the cross-grain bars can be attributed to the bar-to-bar uniformity of the growth ring pattern (see Photo 2), and thus the wood microstructure.

Along-grain Bars			Cross-grain Bars	
Bar Number	E_L (GPa)		Bar Number	E_C (GPa)
3A-L1	15.7		3A-C1	1.11
3A-L2	16.2		3A-C2	1.12
3A-L3	16.6		3A-C3	1.12
3A-L4	17.3		3A-C4	1.08
3A-L5	17.7		3A-C5	1.12
Average =	16.7		Average =	1.11
Std. Dev. =	0.80		Std. Dev. =	0.02

Table 7 – Young's Moduli of unfinished (bare wood) test bars.

B. Impact of Finishes on f_0

Table 8 presents the results of the measurement of f_0 of the test bars after each finish treatment. The impact of the finish steps on f_0 for the along-grain and cross-grain bars is examined both graphically and statistically.

Line graphs (Figures 4 and 5) of the changes in resonant frequency, Δf_0, resulting from finish treatments visually depict the trend for each bar and treatment. The value for Δf_0 of a bar is calculated as f_0 after a treatment, less f_0 of the same bar without finish, i.e. bare wood. The value of Δf_0, rather than f_0, is used to depict the trends because of the bar-to-bar variation in f_0 for the unfinished along-grain bars, as shown in Table 8.

Figure 4 summarizes the trends in Δf_0 with finish step for the along-grain bars and Figure 5 the trends for the cross-grain bars. Each line represents a different bar, identified by its designation number and corresponding color given in the key in Table 9. The finish treatments on the horizontal axis of the figures are designated by a finish step number and brief description of the treatment in the key in Table 9. For the detailed description of the finish treatments see the sections titled **Sealer Application** and **Top Coat Application**. Also note that bars 3A-L3 and 3A-C3 remained unfinished throughout the finish treatment steps to serve as an indicator of the repeatability and precision of the resonant frequency and damping measurements.

Several observations can be made from the data in Table 8 and the charts in Figures 4 and 5:

FINISH STEP:	1	2	3	4	5
	UNFINISHED	SEALER	SEALER	FINISH COAT	FINISH COAT
	WOOD	ON BOTH SIDES	ON TOP SIDE	AFTER 4 DAYS	AFTER 7 WEEKS
	fo (Hz)	fo (Hz)	fo (Hz)	fo (Hz)	fo (Hz)
TEST BAR:					
ALONG-GRAIN					
3A-L1	166	161	158	155	155
3A-L2	168	163	164	161	161
3A-L3*	172	172	173	172	172
3A-L4	175	169	170	168	168
3A-L5	178	172	173	169	169
MEAN (EXCEPT					
FOR CONTROLS):	171	166	166	163	163
CROSS-GRAIN					
3A-C1	100	108	106	105	105
3A-C2	101	108	106	104	108
3A-C3*	101	101	102	102	101
3A-C4	99	106	103	103	105
3A-C5	101	108	106	103	107
MEAN (EXCEPT					
FOR CONTROLS):	100	107	105	104	106

Table 8 — Fundamental resonant frequency, f_0, of test bars after each finish treatment. The mean f_0 is given for each set of test bars (except for the controls) and finish treatment for the purpose of performing significance tests.
***Indicates the unfinished control test bars and the f_0 values.**

1) For both the along-grain and cross-grain unfinished control bars (3A-L3 and 3A-C3), the spread in resonant frequencies was only one Hz for measurements taken over a period of nine weeks. This confirms that the precision and repeatability of the frequency measurement is within ± 1 Hz. It also indicates stability of the equipment for frequency measurement and the constancy of shop conditions such as temperature and relative humidity that could affect the measurements.

2) Compared to the resonant frequencies of the unfinished bars (finish Step 1), the frequencies of the along-grain bars with the finish cured for seven weeks (finish Step 5) are lower (Δf_0 = -7 to -11 Hz; see Table 8 and Figure 4). In contrast, the frequencies of the cured finish at seven weeks for the cross-grain bars (Table 8 and Figure 5) are higher by 5 to 7 Hz (Δf_0 = +5 to +7). Effects similar to these have been observed and reported by previous investigators [18-21].[13] Hains [19] and Schelleng [22] attribute this effect to the value of the Young's modulus for the finish (in this case varnish, equal to about 2 GPa [19]) being between E_C (1 GPa) and E_L (17 GPa) for the spruce (see Table 7). Thus the stiffness of the cross-grain bars is increased and that for the along-grain bars is decreased.

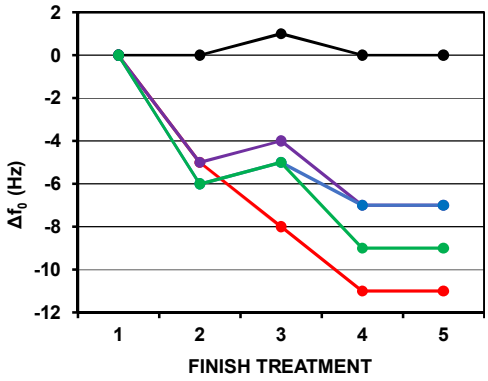

Figure 4 — Line chart of the trend in changes in resonant frequency, Δf_0, with finish treatment for the along-grain bars. See Table 9 for key.

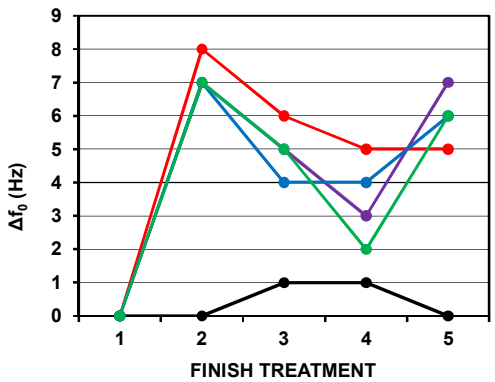

Figure 5 — Line chart of the trend in changes in resonant frequency, Δf_0, with finish treatment for the cross-grain bars. See Table 9 for key.

[13] Hutchins (1991) [18] describes the effect in terms of the change in frequency, whereas Haines (1980) [19], Schleske (1998) [20], and Haines (2000) [21] describe the effect in terms of change in apparent stiffness or Young's modulus, related to frequency by equation (7).

3) The spread in Δf_0 values for the bars increases after treatment step 2 for both the along-grain and cross-grain bars. At Step 2 (sealer coated on both sides) the spread in Δf_0 values is 1 Hz, while for Steps 3 – 5 the spread is 2 to 4 Hz. This indicates that a significant portion of the spread in the data is due to the variation in bar-to-bar application, or removal of the coating (Step 3) as monitored and controlled by weighing with a scale that has a least count of ±0.1 g, limiting the precision as discussed previously.

Finish treatments (horizontal axis): 1) Unfinished sample bars; 2) Sealer both sides; 3) Sealer top only; 4) Finish cured 4 days; and 5) Finish cured 7 weeks.

Sample bar designations and top coat finishes:

3A-L1 and 3A-C1 - Dewaxed Shellac
3A-L2 and 3A-C2 - Modified Dewaxed Garnet Shellac
3A-L3 and 3A-C3 - Bare Wood Control
3A-L4 and 3A-C4 - Guitar Lacquer Aerosol
3A-L5 and 3A-C5 - Modified Dewaxed Shellac Aerosol

Table 9 – Key to line graphs in Figures 4, 5, 6, 7. Each line represents a different sample bar, identified by its designated number, type of top coat finish, and corresponding line and data point color.

4) From the comparison of the values for the bars after Step 2 (sealer both sides) and Step 3 (sealer top only) to Step 5 (finishes at seven weeks), it is seen that the sealer contributes as much to Δf_0, as do the top coats. This indicates that as much care must be taken with application of the sealer coat as with the finish top coats.

C. Statistical Analysis of the Impact of Finishes on f_0

Examination of Figures 4 and 5 suggested the trends in Δf_0 with treatment step, previously discussed. In a few cases the spread in values of Δf_0 for the bars of a treatment step, made it difficult to distinguish whether a treatment step had a significant effect on Δf_0 or not. Paired sample Student's t-Tests at a level of significance of 0.05 (95% confidence) were used to make step-by-step statistical comparisons of the means of f_0 for samples of each finish treatment step. Additionally, comparison of the mean f_0 of Step 1 (no sealer) to the mean of Step 3 (sealer on top side) was included to evaluate the statistical difference between a one-sided sealer, two-sided sealer and no sealer.

The mean of the f_0 values for a treatment step is calculated from the f_0 data in Table 8.[14] The control sample f_0 values were not included in the calculation of a treatment mean, because the control samples did not receive a finish treatment.

A two-tailed t-distribution was used. The t-Test returns a probability, P. If P is less than or equal to the level of significance ($P \leq 0.05$) the difference in the means for the finish treatments is considered statistically significant (i.e. the finish treatment led to a statistically significant change in the mean of f_0).

The analyses were performed with Microsoft Excel statistical analysis tools.[15] The natural pairing of the samples for the t-Test, that is, comparing f_0 for each bar before and after a finish treatment step, discounts differences in f_0 due to, for example, bar-to-bar variation of Young's moduli for the along-grain bars.

Table 10 presents the results of paired sample t-Tests for the along-grain bars and Table 11 the results for the cross-grain bars. For each table: the first column describes the finish step; the second column gives the mean of f_0 for the finish step taken from Table 8; the third column lists P for the results of the

FINISH STEP	MEAN FREQUENCY OF BARS (Hz)	P FOR DIFFERENCE IN MEANS	STATISTICALLY DIFFERENT MEANS?
1-NO FINISH	171		
		P = 0.0003	YES
2-SEALER BOTH SIDES	166		
		P = 1	NO
3-SEALER TOP SIDE	166		
		P = 0.005	YES
4-FINISH AT 4 DAYS	163		
		P = 1	NO
5-FINISH AT 7 WEEKS	163		
1-NO FINISH	171		
		P = 0.008	YES
3-SEALER TOP SIDE	166		

Table 10 – Results of Student's t-Test for finish treatments on the along-grain bars: comparison of the means of f_0 for the treatment steps.

[14] For example, the mean of f_0 values from Table 8 (155, 161, 168, 169) for treatment Step 5 for the along-grain bars is 163 Hz.
[15] For more information on the t-Test as performed by Microsoft Excel data analysis tools, and interpretation of results of the test, refer to Microsoft Excel Help for the t-Test.

t-Test for comparing the means of the two finish steps (e.g. P = 0.005 for the comparison of finish Step 3 to Step 4 in Table 10); and the fourth column states whether the difference in the means is significant (YES) or not (NO).

The top sections of Tables 10 and 11 provide a step-by-step comparison of the means. The lower sections provide a comparison of Step 1 (bare wood) to Step 3 (sealer on top side) to allow comparison of the statistical significance of the sealer on both sides (comparing Step 1 to Step 2) to the sealer on one side (Step 1 to Step 3).

From Table 10 it can be seen that a significant decrease in the resonant frequencies for the along-grain bars occurred at treatment Step 2 (application of the sealer coat on both sides of the bars). Removal of the sealer from one side (Step 3) had an insignificant effect on f_0. Another significant decrease in f_0 occurs at Step 4 (application of the finish top coat). Curing for seven weeks (Step 5) had an insignificant effect on f_0. Note that presence of the sealer on both sides (comparison of Step 1 to 2) or only the top side (comparison of Step 1 to 3) produced a statistically significant decrease in f_0.

Table 11 presents the results of paired sample t-Tests for the cross-grain bars. Table 11 shows that a significant increase in the resonant frequencies for the cross-grain bars occurred at treatment Step 2 (application of the sealer to both sides of the bars), followed by a significant decrease at Step 3 (removal of the sealer from one side). There were no further significant changes in f_0 with the application of the top coats or curing for seven weeks. However, it can be seen that presence of the sealer on either both sides (comparison of Step 1 to 2) or only the top side (comparison of Step 1 to 3) produced a statistically significant increase in f_0. These results suggest that changes in cross-grain resonant frequency are sensitive to the amount of sealer applied.

FINISH STEP	MEAN FREQUENCY OF BARS (Hz)	P FOR DIFFERENCE IN MEANS	STATISTICALLY DIFFERENT MEANS?
1-NO FINISH	100		
		P = 0.003	YES
2-SEALER BOTH SIDES	107		
		P = 0.001	YES
3-SEALER TOP SIDE	105		
		P = 0.103	NO
4-FINISH AT 4 DAYS	104		
		P = 0.08	NO
5-FINISH AT 7 WEEKS	106		
1-NO FINISH	100		
		P = 0.001	YES
3-SEALER TOP SIDE	105		

Table 11 – Results of Student's t-Test for finish treatments on the cross-grain bars: comparison of the means of f_0 for the treatment steps.

From the t-Test analyses, it is clear that the sealer and the top coats play different roles in modifying f_0. For the along-grain bars, the sealer and top coats both contribute to a reduction of f_0. For the cross-grain bars, the sealer increases f_0, while the top coats produce no additional change in f_0. Note that for both the along-grain and cross-grain bars, curing for seven weeks produced no significant change in f_0 as compared to the initial four-day cure.

D. Testing for Differences in the Effect of Top Coats on Δf_0

With respect to the effect of the finish treatments on Δf_0, the question remains: are there significant differences due to the different top coats? To address this question the uncertainty in the Δf_0 values was estimated by calculating the margins of error, and constructing a confidence interval about the mean of Δf_0 for the top coats cured for seven weeks. The procedure is similar to that previously used to estimate uncertainties in the coating areal densities and thicknesses.

The limits of the confidence intervals were calculated from the margins of error, $\xi_{\Delta f}$, and the mean of Δf_0 for treatment Step 5. Calculation of $\xi_{\Delta f}$ requires an estimate of the standard deviation, $s_{\Delta f}$, of the mean, $\Delta f_{0\text{-mean}}$, and the value for the two-tailed t-statistic, k, at a significance level of 0.05, and sample size n:

$$\xi_{\Delta f} = k\,(s_{\Delta f}/\sqrt{n}) \tag{13}$$

The confidence interval is given by:

$$\Delta f_{0\text{-mean}} - \xi_{\Delta f} \le \Delta f_{0\text{-mean}} \le \Delta f_{0\text{-mean}} + \xi_{\Delta f} \tag{14}$$

For the top coats cured for seven weeks, Δf_0 is equal to f_0 for the cured finish less f_0 of the unfinished test bar. Because the spread in the Δf_0 values for the cured top coats may include an effect due to different vibration properties of the top coats, the appropriate estimate of $s_{\Delta f}$ is calculated from Δf_0 data for the bars prior to application of the topcoats, that is, after finish Step 3. The estimate of $s_{\Delta f}$ for the along-grain bars is ±1.7 Hz, and that for the cross-grain bars is ±0.8 Hz. This yields margins of error of ±3 Hz and ±1 Hz respectively. The values of $\Delta f_{0\text{-mean}}$ for the along-grain and cross-grain bars are -9 Hz and +6 Hz. The confidence intervals, according to equation (14), are -12 Hz to -6 Hz for the along-grain bars and 5 Hz to 7 Hz for the cross-grain bars. Values of Δf_0 for the bars, along with the means, margin of errors and confidence intervals, following finish application and curing for seven weeks are given in Table 12.

Top coat Description	Δf_0 (Hz) – Along-Grain Bars	Δf_0 (Hz) – Cross-Grain Bars
Dewaxed Shellac	-11	5
Modified Dewaxed Garnet Shellac	-7	7
Guitar Lacquer Aerosol	-7	6
Modified Dewaxed Shellac Aerosol	-9	6
MEAN, $\Delta f_{0\text{-mean}}$ (Hz) :	-9	6
MARGIN OF ERROR:	±3	±1
CONFIDENCE INTERVAL (Hz):	$-12 \le \Delta f_{0\text{-mean}} \le -6$	$5 \le \Delta f_{0\text{-mean}} \le 7$

Table 12 – Δf_0 values following finish treatment Step 5 (seven weeks cure time) for along-grain and cross-grain bars, along with the means, margins of error, and confidence intervals at the 95% confidence level.

As can be seen from Table 12 the values of Δf_0 for the along-grain and cross-grain bar top coats fit within the 95% confidence intervals. Thus, it is concluded that within the limits of measurement precision, all of the top coats are equivalent with respect to the effect on the changes in the fundamental resonant frequencies.

E. Impact of Finishes on the Damping Q Factor

As with the analyses of the impact of the finishes on f_0 of the bars, similar analyses were performed to quantify the impact of the finishes on the damping, represented by the Q factor. A lower Q represents a higher damping. Table 13 gives the results of the measurement of Q of the test bars after each of the finish treatments.

Line graphs in Figures 6 and 7 visually depict the changes in Q, (denoted as ΔQ) for each bar and treatment. ΔQ for a bar is calculated as Q after a treatment less Q of the same bar without finish. ΔQ rather than Q, is used to examine the trends because of the unfinished bar-to-bar variation in Q, as noted in Table 13. However, in contrast to the bar-to-bar variation in f_0 with the position on the plate from which the along-grain bars were cut, there was no similar trend for Q.

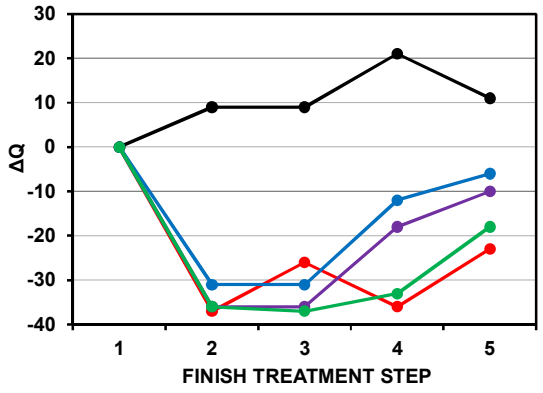

Figure 6 – Line chart of the trend in changes in the damping Q factor, ΔQ, with finish treatment for the along-grain bars. See Table 9 for key.

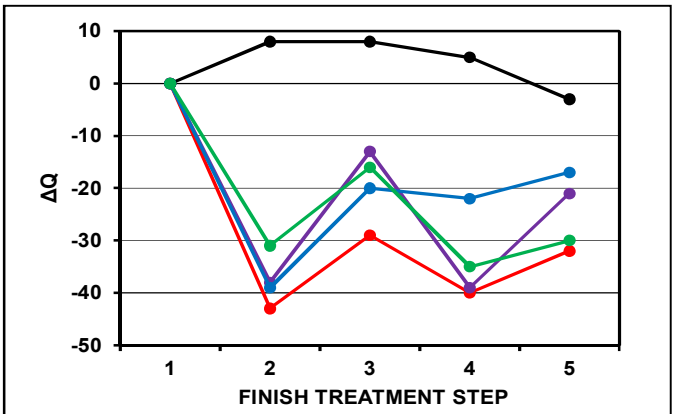

Figure 7 – Line chart of the trend in changes in the damping Q factor, ΔQ, with finish treatment for the cross-grain bars. See Table 9 for key.

Figure 6 summarizes the trends in ΔQ for the along-grain bars and Figure 7 the trends for the cross-grain bars. As in the previous charts for Δf_0, each line represents a different bar, identified by its number and corresponding color given in the key in Table 9. The finish treatments on the horizontal axis of the figures are designated by the finish step number and brief description of the treatment in the key in Table 9.

From Table 13 and the charts of Figures 6 and 7 it can be seen that:

1) The means and standard deviations for measurements of Q for the unfinished control bars taken over a period of nine weeks were: 160 ± 7 for the along-grain bars, and 50 ± 5 for the cross-grain bars. This indicates the precision of the measurement of Q and the repeatability over seven weeks.

2) Compared to Q of the unfinished bars, all of the finish steps resulted in lower values of Q. This is to be expected because of the greater vibrational energy loss due to the plastic-like finish coatings. ΔQ values for the along-grain and cross-bars for the treatment steps are similar. However, because of the much lower Q values for the unfinished cross-grain bars (e.g. 44 for bar 3A-C4) compared to the along-grain bars (e.g. 143 for bar 3A-L4), the finishes have a greater impact on decreasing Q of the cross-grain bars.

FINISH STEP:	1	2	3	4	5
TEST BAR	UNFINISHED	SEALER	SEALER	FINISH COAT	FINISH COAT
NUMBER	WOOD	ON BOTH SIDES	ON TOP SIDE	AFTER 4 DAYS	AFTER 7 WEEKS
	Q	Q	Q	Q	Q
TEST BAR:					
ALONG-GRAIN					
3A-L1	145	108	119	109	122
3A-L2	145	109	109	127	135
3A-L3*	150	159	159	171	161
3A-L4	143	112	113	131	137
3A-L5	162	126	125	129	144
MEAN (EXCEPT					
FOR CONTROLS):	149	114	117	124	135
CROSS-GRAIN					
3A-C1	51	8	22	11	19
3A-C2	47	9	34	8	26
3A-C3*	46	54	54	51	43
3A-C4	44	5	24	22	27
3A-C5	46	15	30	11	16
MEAN (EXCEPT					
FOR CONTROLS):	47	9	27	13	22

Table 13 – Damping Q factor of test bar samples after each finish treatment. For the purpose of performing significance tests, the mean Q is given for each set of samples (except for the controls) and finish treatment.

***Indicates the unfinished control samples.**

It should be noted that lower Q values (increased damping) are not necessarily unfavorable for guitars. Although lower Q values may lead to less sustain and a lower loudness index, a lower Q, because of the larger bandwidth, may also smooth the spectral response of top resonances, leading to more balanced tonal qualities [23].

3) Applying the sealer to both sides of the bars (finish Step 2) had the greatest effect for decreasing the value of Q. After removing the sealer from the back sides of the bars, Q increased for the cross-grain bars, but not for the along-grain bars. Curing the finish seven weeks led to larger values of Q for the along-grain bars but not for the cross-grain bars.

FINISH STEP	MEAN Q OF BARS	P FOR DIFFERENCE IN MEANS	STATISTICALLY DIFFERENT MEANS?
1-NO FINISH	149		
		P = 0.0001	YES
2-SEALER BOTH SIDES	114		
		P = 0.40	NO
3-SEALER TOP SIDE	117		
		P = 0.35	NO
4-FINISH AT 4 DAYS	124		
		P = 0.015	YES
5-FINISH AT 7 WEEKS	135		
1-NO FINISH	149		
		P = 0.001	YES
3- SEALER TOP SIDE	105		

Table 14 – Results of Student's t-Test for finish treatments on the along-grain bars – comparison of the means of Q for the treatment steps.

F. Statistical Analysis of the Impact of Finishes on Q

The impact of finishes on the damping Q factor was examined by the same statistical techniques used to examine the impact of finishes on f_0. A paired sample Student's t-Test at a level of significance of 0.05 was used to compare the means of the Q values for the treatment steps. Table 14 presents the results of the paired sample t-Test for the along-grain bars, and Table 15 the results for the cross-grain bars.

For each table: the first column describes the finish step; the second column gives the mean of Q for the finish step taken from Table 8; the third column provides P for the results of the t-Test for comparing the means of the two finish steps (e.g. P = 0.005 for the comparison of finish Step 2 to Step 3 in Table 15); and the fourth column states whether the difference in the means is significant (YES) or not (NO).

The top section of each table provides a step-by-step comparison of the means. The lower section provides a comparison of Step 1 (bare wood) to Step 3 (sealer on top side) to allow comparison of the statistical significance of the sealer on both sides (comparing Step 1 to Step 2) to the sealer on one side (Step 1 to Step 3).

FINISH STEP	MEAN Q OF BARS	P FOR DIFFERENCE IN MEANS	STATISTICALLY DIFFERENT MEANS?
1-NO FINISH	47		
		P = 0.0006	YES
2-SEALER BOTH SIDES	9		
		P = 0.005	YES
3- SEALER TOP SIDE	27		
		P = 0.068	NO
4-FINISH AT 4 DAYS	13		
		P = 0.061	NO
5-FINISH AT 7 WEEKS	22		
1-NO FINISH	47		
		P = 0.011	YES
3- SEALER TOP SIDE	27		

Table 15 – Results of Student's t-Test for finish treatments on the cross-grain bars – comparison of the means of Q for the treatment steps

From Table 14 it can be seen that a significant change in Q for the along-grain bars occurred for treatment Step 2 (coating with the sealer coat on both sides of the bars). Removal of the sealer from one side (Step 3) had an insignificant effect on Q, as did application of the top coat with a cure time of 4 days (Step 4). However, curing of the top coats for seven weeks was found to significantly increase the value of Q for the along-grain bars. Note that the effect of the sealer on both sides (comparison of Step 1 to 2) and only the top side (comparison of Step 1 to 3) were equivalent, producing a statistically significant decrease in Q.

Table 15 shows that Q for the cross-grain bars significantly decreases with application of sealer to both sides (finish Step 2), and significantly increases with the removal of the sealer from the back side (finish Step 3). At the 95% confidence level there is no further statistically significant change in Q due to finish Steps 4 (P = 0.068) and 5 (P = 0.061) for the chosen level of significance of P=0.05). However, it can be seen that presence of the sealer on both sides (comparison of Step 1 to 2) or only the top side (comparison of Step 1 to 3 in the lower section of Table 15) leads to a statistically significant decrease in Q when compared to the value of Q for the unfinished bars.

Top coat Description	ΔQ – Along-Grain Bars	ΔQ – Cross-Grain Bars
Dewaxed Shellac	-23	-32
Modified Dewaxed Garnet Shellac	-10	-21
Guitar Lacquer Aerosol	-6	-17
Modified Dewaxed Shellac Aerosol	-18	-30
MEAN ΔQ:	-14.3	-25.0
MARGIN OF ERROR:	±8.3	±11.2
CONFIDENCE INTERVAL:	$-23 \le \Delta Q_{MEAN} \le -6$	$-36 \le \Delta Q_{MEAN} \le -14$

Table 16 – ΔQ values following finish treatment Step 5 (seven weeks cure time) for along-grain and cross-grain bars, along with their mean, margin of error, and confidence intervals at the 95% confidence level.

G. Testing for the Differences in the Effect of Top Coats on Q

The impact of the different top coat finishes on the change in Q (ΔQ) was examined by the same statistical techniques used to examine the impact of finishes on f_0. The uncertainty in the ΔQ values was estimated by calculating the margins of error, and constructing a confidence interval about the mean of ΔQ for the top coats cured for seven weeks.

For calculation of the margins of error, the standard deviation $s_{\Delta Q}$ was estimated from the data for ΔQ (Q for Step 3 less Q for Step1) in Table 13. The estimated value of $s_{\Delta Q}$ for the along-grain bars was 5.2 and that for the cross-grain bars was 7.0. The margins of error, calculated according to equation (13), are ±8.3 for the along-grain and ±11.2 for the cross-grain bars.

Values of ΔQ for the bars, along with the means, margins of error and confidence intervals, following finish application and curing for seven weeks are given in Table 16.

As can be seen from Table 16 the values of ΔQ for the along-grain and cross-grain bar top coats fit within the 95% confidence intervals. Thus, it is concluded that within the limits of measurement precision all of the top coats are equivalent with respect to the effect on the change in the damping quality factor Q.

IV. Conclusion

A key finding of this study is that all of the top coat finishes, both the evaporative finishes (dewaxed shellac and guitar lacquer) and reactive finishes (modified dewaxed shellac and modified dewaxed shellac aerosol), applied over the same sealer, produce equivalent changes in the properties of fundamental vibrational frequency, f_0, and damping, Q, of the spruce test bars. Specific effects of the finishes on f_0 and Q, supported by statistical analyses, show that both the sealer and top coats affect f_0 and Q, but in different ways:

1) The sealer alone produces significant changes in both f_0 and Q for the two grain orientations of the spruce test bars: the along-grain f_0 decreases; the cross-grain f_0 increases, and Q for both grain orientations decreases.

2) The finish top coats affected f_0 for only the along-grain bars. The along-grain f_0 decreases with top coat application. At the 95% confidence level, application of the top coats have no significant effect on the cross-grain f_0.

3) Compared to Q for the sealer coating, all of the top coats cured for seven weeks showed an increase in Q for the along-grain bars. Q for the cross-grain bars cured for seven weeks showed no significant increase.

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