The violin bridge as filter

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The violin bridge filter role was investigated using modal and acoustic measurements on 12 quality-rated violins combined with systematic bridge rocking frequency f_{rock} and wing mass decrements Δm on four bridges for two other violins. No isolated bridge resonances were observed; bridge motions were complex (including a "squat" mode near 0.8 kHz) except for low frequency rigid body pivot motions, all more or less resembling rocking motion at higher frequencies. A conspicuous broad peak near 2.3 kHz in bridge driving point mobility (labeled BH) was seen for good and bad violins. Similar structure was seen in averaged bridge, bridge feet, corpus mobilities and averaged radiativity. No correlation between violin quality and BH driving point, averaged corpus mobility magnitude, or radiativity was found. Increasing averaged-over-f_{rock} Δm(g) from 0 to 0.12 generally increased radiativity across the spectrum. Decreasing averaged-over-Δm f_{rock} from 3.6 to 2.6 kHz produced consistent decreases in radiativity between 3 and 4.2 kHz, but only few-percent decreases in BH frequency. The lowest f_{rock} values were accompanied by significantly reduced radiation from the Helmholtz A0 mode near 280 Hz; this, combined with reduced high frequency output, created overall radiativity profiles quite similar to "bad" violins among the quality-rated violins. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2207576]

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I. INTRODUCTION

> "*It is difficult to imagine the reason of this; how it is that a little piece of maple, which merely serves to keep the strings off the finger-board, should have such a powerful effect on the tone of the instrument to which it is not fastened in any way, being merely kept in place by the pressure of the four strings*"
> (Heron-Allen, 1884).

The bridge—a seemingly minor, ~0.002 kg substructure on top of a ~0.4 kg violin—has been considered a vital ingredient of good violin tone for centuries. In his remarkable summary book of everything known about violins and their construction up to 1884, Heron-Allen then proceeded to provide an answer. "*The first explanation of this influence must be sought for in the fact that it is the principal channel by which the vibration of the strings pass, to the belly…, and to the back.…*"[1] Obviously the prominent role of the bridge as the energy "gatekeeper" has been recognized for a long time. It is the first of the two primary, independent components of violin sound. The second filter component—the subsequent conversion of corpus vibrational energy to acoustic energy—has now been addressed quite generally from the behavior of the violin normal mode radiation efficiency over the audible range, the ratio of radiation damping to total damping, and an effective critical frequency for the violin.[2,3]

Numerous experimental studies of bridge motion have been published over the years,[4,5] but one aspect of the bridge has dominated discussion over the last 30 years or so, a broad peak in driving point mobility (input admittance) first observed as an impedance minimum by Reinicke,[6] the so-called "bridge-hill" near 3 kHz thought to be linked to the first in-plane rocking mode of the clamped-foot bridge near that frequency. Little work has been done however on the bridge's actual dynamic mechanical behaviors in relationship to corpus vibrations and subsequent radiation from the violin.

Jansson and co-workers have been leaders in experimental analysis of the bridge and its effects on violin response for many years,[7–13] stating early on that there was a correlation between the quality of a violin and the prominence of the bridge-hill. Of late their attention has turned to quantifying the effect of bridge modifications on the driving point mobility spectrum. In an especially revealing experiment they replaced the standard bridge (with heart and hip cutouts) by a solid bridge, which increased the rocking mode frequency from ~3 to ~8 kHz. Surprisingly the bridge-hill remained near 2.5 kHz.[12] (In a less declaratory experiment Reinicke in 1973 observed no significant movement in the impedance minimum when wedges were inserted into the side slots to stiffen the bridge.[6]) For the first time an experiment clearly showed that the bridge was not the predominant influence on the "bridge-hill," hence future references will be to the BH peak.

Following this experiment Beldie modeled the generalized effects of localized top plate stiffness in addition to bridge stiffness, concluding that material properties of the top plate where the bridge feet rest dominated measured BH behavior, with relatively minor contributions from the bridge itself.[14] Subsequently in an extensive experimental series Durup and Jansson investigated the effect of cutting rectangular segment *f*-holes into rectangular spruce plates, concluding that without *f*-holes no bridge-hill was seen.[13]

Modes of the various substructures do influence overall structural response, to some extent in proportion to their fraction of the overall mass, as they are subsumed into the

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overall response of the violin. The bridge however falls into a special category because it is the string-to-corpus energy conduit/filter. In this work modal analysis and radiativity measurements on quality rated violins in an anechoic chamber were combined with systematic bridge waist and wing mass trimming experiments to investigate the effect of this filter on violin radiativity. This comprehensive approach was designed to provide experimental answers to questions such as: (1) does the bridge substructure demonstrate recognizable in-plane normal mode resonances while on the playable violin, (2) are enhanced bridge motions related to enhanced corpus vibrations and radiativity, (3) is there a relationship between BH magnitude and violin quality, (4) is the BH frequency f_{BH} sensitive to the rocking frequency f_{rock} of the bridge, (5) are there general radiativity trends arising from bridge waist (stiffness) or wing mass trims?

II. EXPERIMENT

A. VIOCADEAS measurements

The VIOCADEAS zero-mass-loading calibrated experimental measurements have been described elsewhere in considerable detail[15] (and references therein). Here only essentials will be presented. Simultaneous vibration and radiation measurements were performed in an anechoic chamber on violins hung by two thin elastics in an approximate "free-free" condition. The frequency range encompassed the BH hill near 2.3 kHz and the critical frequency for "good" violins.[2] Violin quality ratings for the 12-violin database were all by an outstanding professional violinist[15] following Weinreich's general 3-category scheme[16] of student (our bad category—rating 1–3), decent professional instrument (good category—rating 4–7), and fine solo instrument (excellent category—rating 8–10). The good violin data shown in plots were from three violins rated 7, while the bad were rated 2,3,3.

The calibrated measurements incorporated 9 points on the bridge proper, plus multiple points along a line on the corpus directly in front of the violin bridge from which the motion of each bridge foot was extracted. Earlier uncalibrated "free-free" vibration measurements on 20 violin bridges with a zero-mass-loading microphone were used to help categorize in- and out-of-plane bridge normal modes.[17]

Force hammer impacts at the driving point on the bridge G-corner in its plane were directed parallel ($F_{\|}$) or approximately perpendicular ($F_{\perp}$) to the plane of the violin. Tested violins were playable although chin and shoulder rests were removed. No damping was applied to strings at tension ($A = 440$ Hz). The scanning laser picked up motion along the beam direction and generated mobility (velocity/force: complex) transfer functions $Y(\omega)$ for approximately 500 points over the corpus (top-ribs-back); bridge (9 points), tailpiece and neck-fingerboard measurements were in two perpendicular directions. Simultaneously a rotating 13-microphone array collected pressure data and generated radiativity (pressure/force; complex) transfer functions $R(\omega)$ at 266 points over a sphere. Bridge mode classifications as normal or complex were made using the mode animation capability in the modal analysis program.

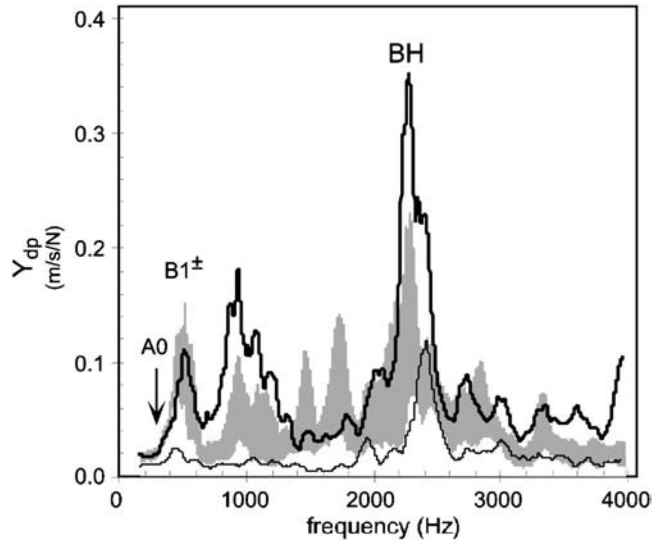

FIG. 1. Min-max driving point mobility magnitude for good (shaded) and bad violins (curves); A0,B1$^{\pm}$,BH noted.

The proposed linkage of a prominent BH driving point mobility (input admittance) Y_{dp} with good sound quality was examined through a plot of minimum-maximum Y_{dp} ranges for good and bad violins (Fig. 1; low-lying strongly radiating "signature modes" labeled: A0, the compliant wall Helmholtz radiator (~280 Hz) and B1$^{\pm}$, the first corpus bending modes nominally between 450 and 550 Hz). Driving point spectra did not show strong A0 excitation. The most prominent structure was the BH peak, and the largest BH peak was for a bad violin, with variability between bad violins being considerably larger than for good violins.

The 250-Hz (or other) band averages of driving point mobility Y_{dp}, averaged-over-bridge mobility $\langle Y_{brg} \rangle$, averaged-bridge-foot mobility $\langle Y_{brgft} \rangle$, averaged-over-corpus mobility $\langle Y_{corpus} \rangle$ and averaged-over-sphere radiativity $\langle R \rangle$ ($\langle\ \rangle$ denotes rms average) were computed directly from the spectra, not by averaging individual normal mode properties over these bands as was done in previous work. This greatly speeded data analysis, bypassed fitting and mode overlap problems and statistical fluctuations associated with the small numbers of modes in a band while giving comparable results.

As expected modal analysis results showed that vibrational energy transfer from strings to violin corpus was predominantly through the bridge, with bridge impedance ranging from 0.01× to 0.1× the nut or tailpiece impedance. Henceforth we assume the only important path for string energy to reach the corpus will be through the bridge.

B. Bridge Waist - Wing Mass Trims

The effects of bridge waist and wing mass trimming on violin radiativity were examined in a systematic way at the Oberlin Violin Acoustics Workshops in 2004 and 2005. The VIOCADEAS support fixture and force hammer excitation apparatus were removed as a unit from the anechoic chamber and mounted temporarily on a base that incorporated 5 evenly-spaced calibrated microphones in a semicircular array ($r = 0.3$ m), at 30° intervals from 15° to 165°, oriented perpendicular to the top plate in the plane of the bridge. Eight Sonex 15 cm foam wedge absorbers were placed underneath the violin to reduce nearest-surface floor reflections. Low mass (0.5 g) accelerometers were placed at each bridge foot in front of the bridge. An 8-channel data acquisition system was used to collect accelerances from both bridge feet and radiativity transfer functions from the 5 microphones. The averaged 5-microphone radiativity will henceforth be labeled as a partial radiativity $\langle R_{\text{part}} \rangle$ to distinguish it from the averaged-over-sphere $\langle R \rangle$.

In the Oberlin 2004 experiment, two violins, an Andreas Guarneri (1660) and a Gregg Alf (2003), were fitted with four bridges each. No changes other than the sequenced bridge modifications were made to either instrument. The rocking mode frequency f_{rock} was measured off-violin using a separate apparatus incorporating a piezo-film contacting the bridge top along with a bridge-foot clamping vise. The bridge blank tops were first trimmed down to give the proper string height for each violin, and then each waist was trimmed to give $f_{\text{rock}}=3.6$ kHz (nominal). Three bridges then had their wing mass decremented by $\Delta m=0.04$, 0.08, and 0.12 g, all from the same location in the bridge wings, and the waist was again trimmed slightly to drop f_{rock} back to 3.6 kHz. One bridge in each set of four had no wing-mass decrement and was labeled $\Delta m=0$. Finally, waist thicknesses only were trimmed in successive stages to get $f_{\text{rock}}=3.4$, 3.2, 3.0, 2.8 kHz. Altogether 20 $\langle R_{\text{part}} \rangle$ measurements were made for each violin during the sequential modification process.

Mass removal from the waist was much more effective in changing f_{rock} than from the wings: $\Delta f/\Delta m \approx 24 \pm 14$ kHz/g vs. 0.75 ± 0.03 kHz/g, convincing support for simplified bridge models separating the bridge into a top mass and waist spring—irrespective of boundary conditions for the feet. Other experimental systematics from waist trimming $(2.8 \leq f_{\text{rock}} \leq 3.6$ kHz) were values for: (1) f_{rock} changes versus waist thickness x, $\Delta f/\Delta x \approx 180$ Hz/mm, (2) bridge mass changes for waist trims, $\Delta m/\Delta x \approx 0.009$ g/mm, (3) waist trims from 16.3–17.8 mm to 11.8–13.1 mm, 4.7 mm on average, (4) mass changes associated with waist trimming from 0.014 to 0.068 g, 0.043 g on average. The 40 separate bridge modifications/measurements in the 2004 two-violin experiment were made as rapidly as possible, precluding qualitative judgments. The 2005 experiment, where f_{rock} was dropped from 3.4 to 3.0 to 2.6 kHz but $\Delta m=0$, used only one bridge on one violin, but the instrument was played for a small group of listeners after each bridge trim for qualitative evaluation.

Using Oberlin 2004 data a 4×5 data "R matrix" can be created for each frequency or frequency band from $\langle R_{\text{part}} \rangle$ spectra, but it is completely impractical to present these matrices for any more than a few important bands for each violin to demonstrate complexities accompanying simultaneous f_{rock} and Δm changes. To examine any generalized f_{rock} or Δm trends the R matrices were reduced to a single row or column by averaging over f_{rock} for one bridge (Δm = constant) to scrutinize general $\langle R_{\text{part}} \rangle$ vs Δm effects, and by averaging over Δm for four different bridges (f_{rock} = constant) to scrutinize general $\langle R_{\text{part}} \rangle$ vs f_{rock} effects.

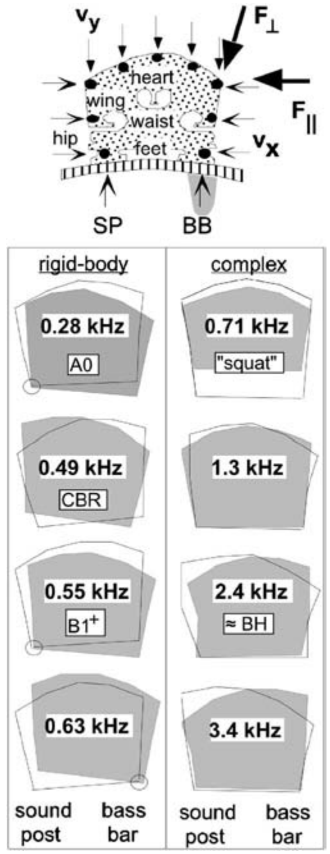

FIG. 2. (Top) bridge shape, force-response positions and directions (soundpost SP and bassbar BB from corpus); (bottom) motion extremes up to 4 kHz (A0, CBR, B1^{+}, "squat," $f \approx f_{\text{BH}}$ labeled; ○ — rigid body SP or BB pivot.

III. RESULTS

Experimental results are presented in two main sections: (1) modal-acoustic analysis for dynamic and radiative behaviors of the violin or any particular substructure to understand energy transmission through the violin, and (2) systematic waist and wing mass trims to examine bridge filter effects on radiativity.

A. Modal analysis of bridge vibrations

Figure 2 shows the position and measured mobility direction(s) for each bridge point, including the driving point. Since the bridge feet were in intimate contact with the top plate, it was assumed that corpus motion measured immediately adjacent to the bridge feet could be used as a direct measure of bridge foot motion in the vertical direction; separate horizontal motion measurements were made on the sides of the bridge feet. The energy introduced at the bridge travels through an energy chain from driving point → bridge → bridge feet → corpus → radiation. Superimposing the mobility responses of each link it is possible to see if characteristic structures in driving point mobility spectra "migrate" from bridge to corpus to radiativity. Near f_{BH} modal average radiation efficiencies are nearing 1.[2] Since f_{BH} is also close to the ear's sensitivity maximum, such peaks should generally be audible.

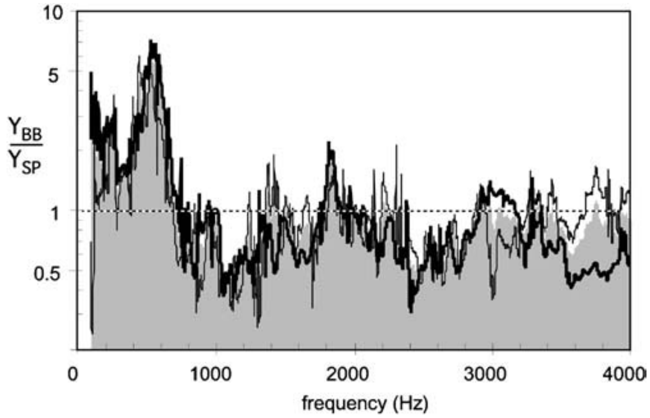

FIG. 3. Bassbar-soundpost bridge foot mobility ratio for $F_{\parallel}$ driving point excitation. (Shaded — 12-violin average; lines: thick - good, thin — bad).

1. Bridge motions on the violin

The observed bridge motions for all twelve violins were basically the same: (a) at frequencies <0.7 kHz the bridge generally pivoted as a rigid body around the soundpost or bass bar foot (exception—the CBR mode where both feet were active) with little deformation, (b) above ~ 0.7 kHz, to 4 kHz, motions were complex. No normal mode bridge motions—strong, $0-180°$ bridge motions unaccompanied by other substructure peaks—were seen. A sampling of observed bridge motions is presented in Fig. 2 for one violin.

In all 12 violins bass bar foot motion predominated below 600 Hz; above 600 Hz generally the sound post side was more active. Note however that relatively little foot motion was seen above 1 kHz (Fig. 2). The ratio of bass bar to soundpost mobilities shows this trend for the 12-violin average, as well as just the good or bad 3-violin subsets (Fig. 3).

2. Independent bridge modes?

Is the bridge capable of maintaining a vibration mode independent of the corpus and strings between which it resides? If so, there would be a peak in bridge mobility that does not coincide with any corpus or string mode peaks. Such a possibility was eliminated straightforwardly up to 4 kHz by examination of composite plots of Y_{dp}, $\langle Y_{brg} \rangle$, $\langle Y_{brgft} \rangle$ $\langle Y_{corpus} \rangle$, and $\langle R \rangle$; bridge mobility peaked *only* when corpus mobility peaked. This observation, consistent with recent simulations,[14,18] is unsurprising given the low mass of the bridge compared to the vibrating (varying boundary condition) corpus on which it rides, or even in comparison to the strings, which *in toto* have a mass similar to the bridge. Including tailpiece and neck-fingerboard averages in such plots also shows that only the corpus radiates significantly (cf. Fig. 1, Ref. 3).

One interesting complex mode where the bridge appeared to have a "squat" behavior in animation (see Fig. 2) was observed for 9 of the 12 violins tested. It fell far below the in-plane bridge rocking mode frequency, not above as would be expected for an in-plane mode. The overall motion and frequency placement were consistent with the first *out-of-plane* bending mode where the strings and top plate create boundary condition constraints on transverse motion at opposite ends of the bridge.

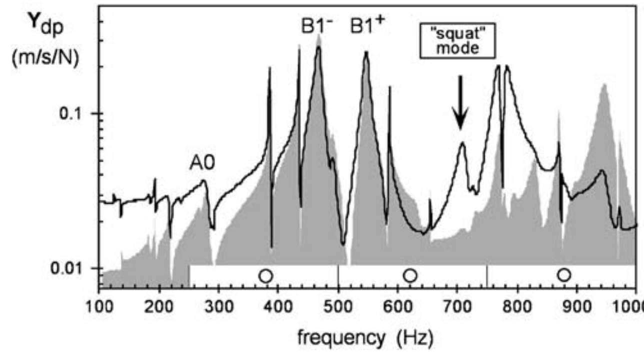

FIG. 4. $F_{\parallel}$ (shaded curve) and $F_{\perp}$ (solid line) driving point excitation shows "squat" mode near 700 Hz. (Major radiators A0, $B1^-$, and $B1^+$ labeled; note 250 Hz bands and band centers (○).

The motion suggests being more strongly excited by $F_{\perp}$ than $F_{\parallel}$ strikes, as was confirmed by experiment (Fig. 4). Similar response differences near this frequency were seen earlier by Trott.[19]

3. Energy chain

To illustrate how the driving point BH structure (Fig. 1) appears throughout the energy chain a sequence of 250-Hz band averages for good and bad violins is presented in Fig. 5 for the driving point Y_{dp}, bridge ($\langle Y_{brg} \rangle$), bridge feet ($\langle Y_{brgft} \rangle$), corpus ($\langle Y_{corpus} \rangle$), and averaged-over-sphere radiativity $\langle R \rangle$. A distinct BH peak near 2.3 kHz is evident throughout the chain, in the bad as well as good, being somewhat larger for the bad in Y_{dp} (although error bars overlap) and Y_{brg}. This result disagrees markedly with the quality association current in the literature.

4. BH mobility and radiativity versus quality

Overall the bad violin radiativity curve in Fig. 5(e) has a larger maximum-minimum range and falls off more on either side of the BH structure near 2.3 kHz. Can some audible difference in sound be ascribed to the difference between our good-bad broad-band excitation radiativity curves, even though the general string driving force is sawtooth-harmonic in character? For discussion and comparison purposes we use a simplified sound characterization scheme based on that of Dunnwald[20] with additional contributions from Meinel,[21] where relatively strong radiation in individual bands is associated with a certain general character to the sound: 190–650 Hz — "sonorous, full sound" (this band includes the first corpus bending modes $B1^-$ and $B1^+$; Dunnwald also notes the importance of a relatively strong A0 near 280 Hz); 650–1300 Hz — "nasal, boxy"; 1300–4200 Hz — "brilliant, clear"; 4200–6400 Hz — "harsh."

The band-by-band ratio of radiativities shown in Fig. 6 is useful for examining good-bad differences. In this ratio any common driving force cancels for broad-band or harmonic excitation. A significant difference between the quality classes appears only for a few individual 250 Hz bands, viz., 375, 1625, and 3375 Hz bands. Ratios in the BH region (2125–2625 Hz) do not differ significantly. The ~ 3.4 kHz region falls where the lower effective critical frequency of

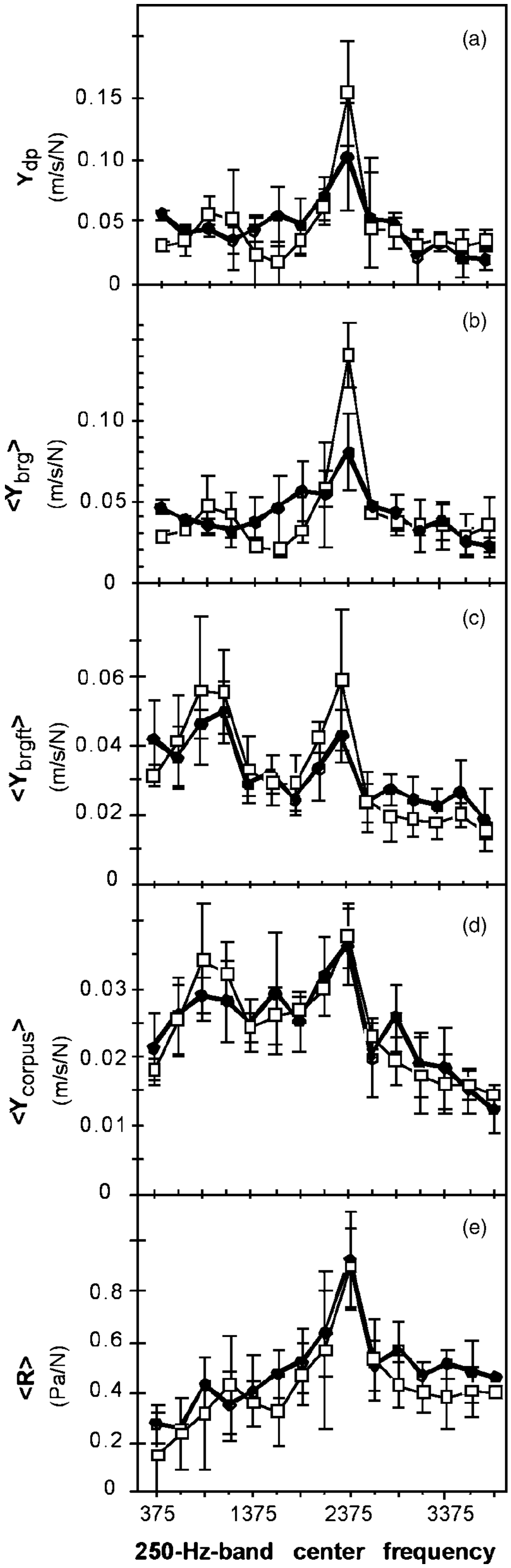

FIG. 5. Driving point (a), bridge (b), bridge feet (c), corpus (d), radiativity (e) for good (thick line, ●) and bad (thin line, □) violins. (1 s.d. errors shown).

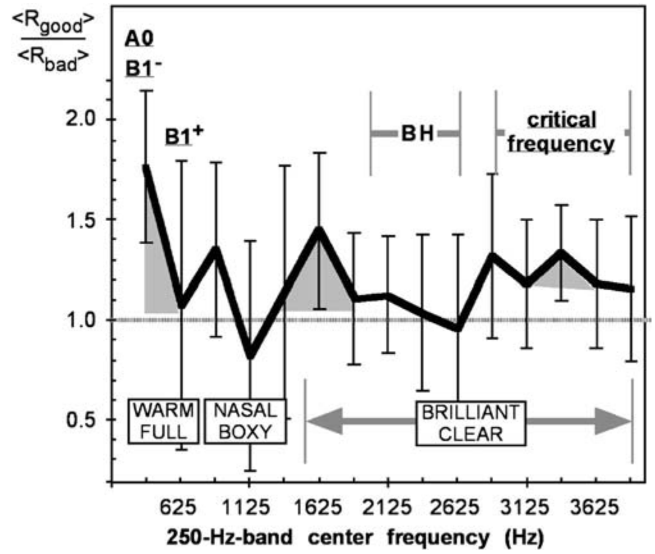

FIG. 6. Good-bad $\langle R \rangle$ ratio (1 s.d. errors). (Noted: BH, critical frequency, boxed quality descriptors, signature modes A0, $B1^{-}$, and $B1^{+}$; shading denotes significant difference from 1).

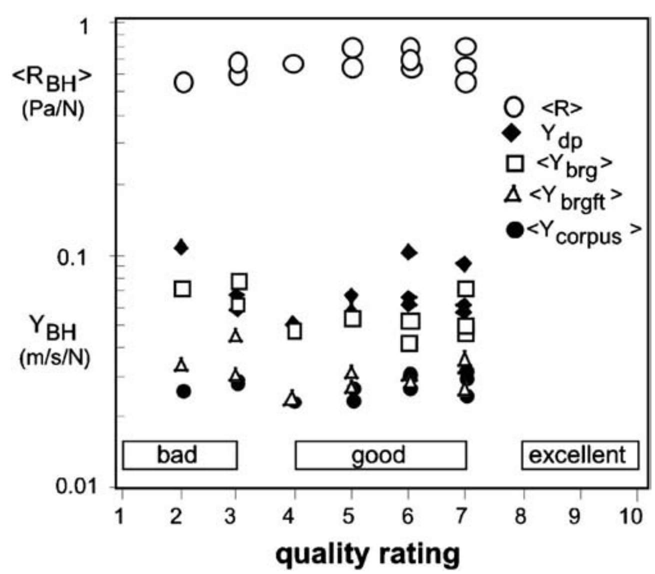

FIG. 7. Driving point(◆), average bridge(□), bridge feet(△), and corpus (●) BH mobility magnitudes and average BH radiativity(○) for 12 violins vs violin quality.

these good violins can enhance radiativity,[2] a relative enhancement actually reinforced by holding/playing the violin.[3]

An important question concerning possible significant good-bad differences in band-average radiation efficiency near f_{BH} can be answered directly from the data in Fig. 5: $\langle Y_{\mathrm{corpus}} \rangle$ and $\langle R \rangle$ magnitudes are within error the same for good and bad violins, hence the BH radiation efficiency — computed from the $\langle R^2 \rangle / \langle Y^2_{\mathrm{corpus}} \rangle$ ratio[22] — does not vary significantly between good and bad violins.

To look for trends versus violin quality Y_{dp}, $\langle Y_{\mathrm{brg}} \rangle$, $\langle Y_{\mathrm{brgft}} \rangle$, $\langle Y_{\mathrm{corpus}} \rangle$, and $\langle R \rangle$ BH magnitudes were plotted for the 12 violins in Fig. 7. The 7-quality violins were not significantly different from the 2/3-quality violins, e.g., at the extremes the three 7-quality good violin magnitudes covered a range that usually overlapped the 2/3 violin values. While one might argue that these are poor statistics, a better argument might be that even in this small sample there are already exceptions — both inter- and intra-violin quality class — to any presumed correlation between violin quality and a large BH peak. The data shown in Figs. 5–7 that pertain to the presumed relationship between BH magnitude and violin quality can be summarized briefly as showing no experimental correlation between the driving point or corpus mobility, or the radiativity, or the radiation efficiency that is significantly different between good and bad violins. Rather, the good-bad differences so far appear to lie in the strengths of the other acoustically important regions *relative* to BH.

B. Bridge waist and wing mass trims

Waist-wing trimmings entailed removal of ≤ 0.12 g from the bridge; no effect was seen on corpus mode frequencies when proper string tension was maintained, hence mode shapes and radiation efficiencies should remain the same. Under these conditions $\langle R_{\text{part}} \rangle$ measurements were quite reliable for investigating intra-violin radiativity changes due to systematic f_{rock} and Δm variations. They were also reliable for inter-violin mode comparisons below ~ 0.7 kHz, since radiativity is close to isotropic when $\lambda >$ violin dimensions.

Above 1 kHz inter-violin broadband comparisons of $\langle R_{\text{part}} \rangle$ become more reliable than individual spectra because coincidental microphone placements at minima for one mode should tend to average out with equally coincidental placements at another mode's maximum within each band. Because the cavity mode A0 lying at $f \approx 280$ Hz is such an important radiator, and the *only* strongly radiating mode below about 450 Hz, it was isolated for special attention using the average over ±10 Hz around the peak. The lowest band-average now covers 300–500 Hz, with band center at 400 Hz (all higher bands as before).

The R matrix from the Oberlin 2004 experiment provides a systematic framework in which to analyze possible filter effects from bridge waist or wing mass trims (all other violin properties held constant) on radiativity. Filter effects related to f_{rock} variations were the most straightforward to interpret since only one bridge waist was trimmed. Wing mass trims however were over four different bridges, i.e., four different pieces of wood, a possible complication.

1. f_{rock} and the BH frequency

Trimming the waist primarily changed the rocking mode frequency f_{rock}, with little effect on the bridge mass (3.6 to 2.8 kHz, max. $\Delta m = 0.068$ g; average $\Delta m = 0.045$ g). When the bridge was in place on the violin the BH centroid frequency f_{BH} (nominally 2.3 kHz) had a range $\Delta f_{\text{BH}} = 31 \pm 15$ Hz (average over all bridges for both violins) as f_{rock} varied 0.8 kHz, giving $\Delta f_{\text{BH}} / \Delta f_{\text{rock}} \approx 0.04$. Clearly f_{BH} was insensitive to f_{rock} variations, (although the Guarneri was somewhat more sensitive), in agreement with the general conclusions of Ref. 7. A more recent model of Woodhouse[18] incorporating the dynamic properties of the violin underneath a simplified bridge placed on top of a rectangular box without f-holes displayed higher f_{BH}values (~ 2700 to ~ 3500 Hz), far greater changes ($\Delta f_{\text{BH}} \approx 740$ Hz) and sensitivity $\Delta f_{\text{BH}} / \Delta f_{\text{rock}} \approx 0.93$ than experiment. The experiments of Ref. 14 required f-holes in a rectangular spruce plate to display a prominent BH peak while this model did so without f-holes, an interesting inconsistency that clearly warrants a closer look.

2. The R matrix

In the normal listening situation where listeners can be at differing distances, in different rooms, or listening to a recording, etc., the obvious point that the sound intensity varies yet the general character of sound remains (while not forgetting that the ear's frequency response varies with intensity), supports the general argument that the relative strengths of certain frequency bands, i.e., "acoustic profiles," are more important in determining perceived character. In this context comparing $R(\omega)$ radiativity curves over a large portion of the violin's acoustic range is valuable. On the other hand extracting trends from a visual overlay of 20 such $R(\omega)$ curves created in the bridge trim experiment becomes a daunting interpretive situation. Comparison was somewhat simplified by comparing 250 Hz bands, but there are such a large number of these bands that in practice little has been gained. On the other hand if just one particular frequency band was chosen for the R matrix, it would not provide any comparison with other bands. Our practical compromise was to create for each violin R matrices for only three acoustically significant bands: A0 (~ 280 Hz), BH (~ 2300 Hz, lower portion of the "brilliant, clear" band), and the upper portion of the "brilliant, clear" (B-C) band (2500–4200 kHz). These were all bands where significant changes occurred during the bridge trims. The R matrices for each violin are presented in Fig. 8, where the square sizes for the A0, BH, and B-C bands are proportional to the $\langle R_{\text{part}} \rangle$ values in each band. Moving horizontally in each row shows the effect on $\langle R_{\text{part}} \rangle$ of only varying f_{rock} so that one bridge is trimmed successively. Moving vertically in each column shows the effect on $\langle R_{\text{part}} \rangle$ of only Δm varying and here different bridges were employed (see Sec. II B).

Variations of individual $\langle R_{\text{part}} \rangle$ matrix elements before and after modification in Fig. 8 reflect the actual complexity of bridge trims (and of course any associated comparative quality judgments of violins). For example, even for one violin, changing only Δm (moving in only one f_{rock} column) or f_{rock} (moving in only one Δm row), A0 waxes and wanes; a diagonal move — changing f_{rock} and Δm simultaneously — seems quite an uncertain move for a maker in terms of knowing what will happen to $\langle R_{\text{part}} \rangle$, both in magnitude and relative strength, and to the sound. And this is for just one band. The practical difficulty in evolving a violin from a certain sound character to another, more desirable one via a particular bridge modification is apparent.

The many localized variations — e.g., for the Alf violin $\Delta m = 0.12$ g row, BH magnitudes decrease slightly with increasing f_{rock}, whereas for $\Delta m = 0$ they increase, or in the $f_{\text{rock}} = 2.8$ kHz column $\langle R_{\text{part}} \rangle$ drops off in the 0–0.04 Δm transition, increasing again in the 0.04–0.08 transition — tend to bury overall trends. Yet makers have certain general ideas gained from centuries of experience about what a particular bridge trim will do to the sound. This generalized approach presumably is more fruitful since trends common to both violins do appear, e.g., averaged-across-f_{rock} radiativities increase as wing mass decrements increase, albeit with individual exceptions. The averaging-across-rows/columns of the R matrix will be needed to extract any gen-

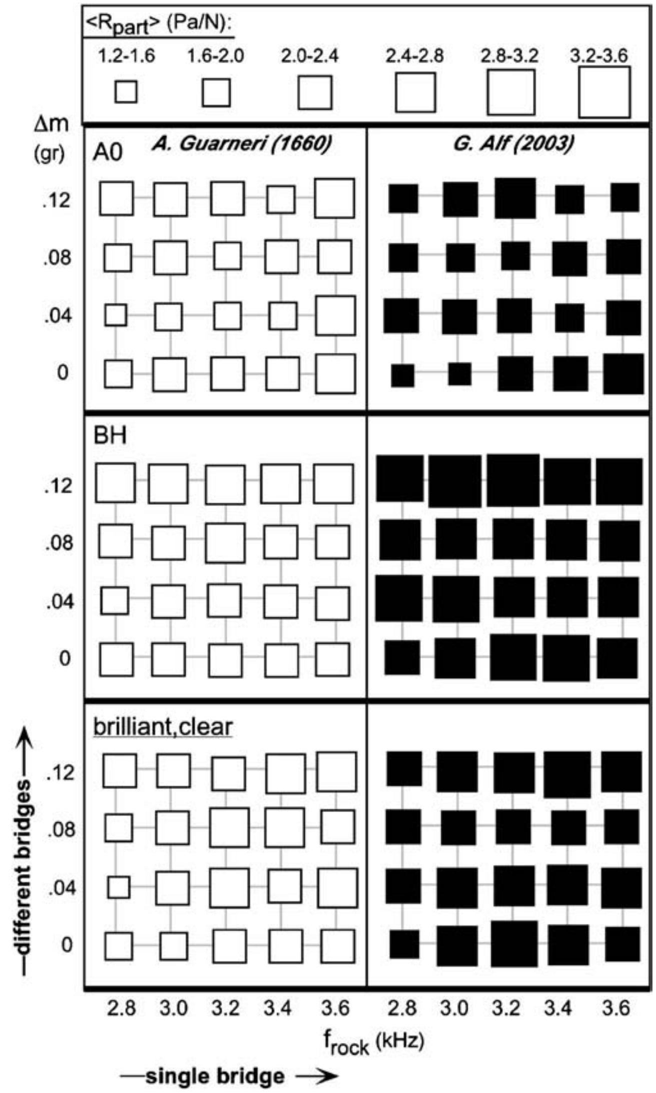

FIG. 8. Δm-f_{rock} *R*-matrices for A0, BH, and "brilliant, clear" bands for A. Guarneri and G. Alf violins. ($\langle R_{\mathrm{part}}\rangle$ stepped, see key.) Note that f_{rock} changes along a row are for a single bridge, while Δm changes in each column are across four different bridges.

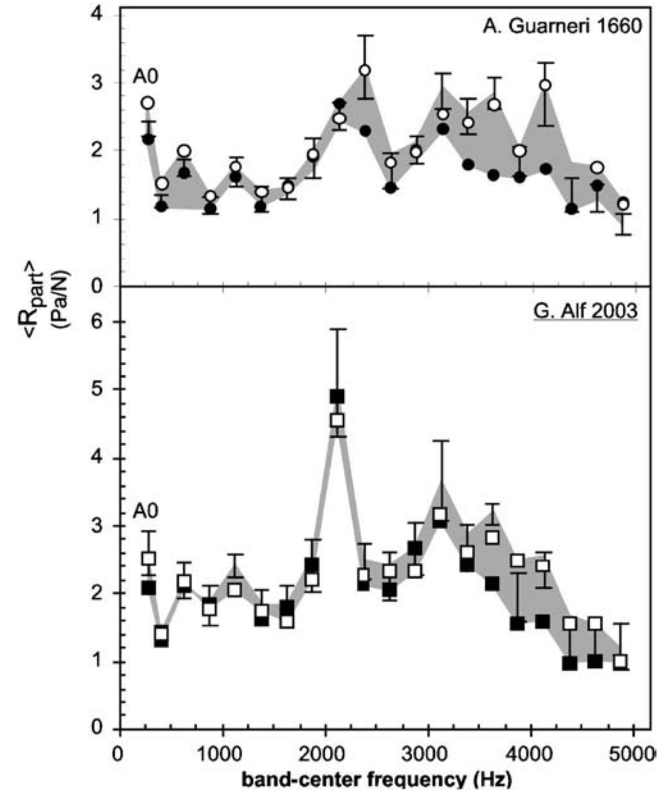

FIG. 9. Effect on partial radiativity of varying f_{rock} from 2.8 (closed symbols) to 3.6 kHz (open symbols), averaged over Δm for four bridges for old Italian (top) and modern violin (bottom). Shaded area min-max curve, all f_{rock}; 1 s.d. errors for 3.2 kHz averages only, no curve). Note — A0 separated from lowest band (see the text).

eral radiativity trends accompanying *just* rocking frequency or wing mass changes.

3. f_{rock} and $\langle R_{\mathrm{part}}\rangle$-$\Delta m$ averaged

The radiativities shown in Fig. 8 showed extensive local fluctuations as f_{rock} or Δm was stepped. To extract generalized trends in $\langle R_{\mathrm{part}}\rangle$ magnitudes and acoustic profiles accompanying changes in f_{rock}, the band-average 2004 data for each f_{rock} value were averaged over all Δm. The averaged radiativity analysis presented in Fig. 9 incorporates: (1) a min-max $\langle R_{\mathrm{part}}\rangle$ shaded curve to highlight regions where waist trims had the largest effect on $\langle R_{\mathrm{part}}\rangle$ and how these evolve with frequency, (2) extreme curves for $f_{\mathrm{rock}}=2.8$ and 3.6 kHz to act as a guide to interpreting generalized trends, and (3) standard deviation error bars for the intermediate 3.2 kHz curve as a nominal statistical measure of variability in the Δm average. Certain general criteria were used to judge the relationship of the extreme curves to the min-max curve: (a) if the extreme curves "bracket" the min-max curve consistently over a region this was taken as *prima facie* evidence for a consistent general trend in this region (e.g., the ~3000 Hz region), (b) if the extreme curves were centered in the min-max curve, further analysis was needed to see if there was a peak in the f_{rock} range, (c) if the 3.2 kHz error bars fell outside the minimum and maximum in a band or region, no significance was attached to the extreme curve variations (e.g., 1875 Hz band), and (d) general trend comments about a wide region could be made irrespective of an individual band's deviation from this trend.

The min-max shaded regions for both violins in Fig. 9 clearly show the most prominent waist trim effects were in the 3000–4200 Hz region where the ear is most sensitive, least prominent near 1500 Hz, and, somewhat surprisingly, rising again at A0. The fact that the extreme f_{rock} curves typically lie at or near the maximum or minimum over important regions leads us to infer certain general trends versus f_{rock}: both A0 and the nominal 2000–4200 Hz region generally weakened as f_{rock} decreased. Waist trims affected the BH position and amplitude more noticeably on the old Italian than on the modern instrument.

Some tendency for increased radiativity above 4200 Hz — the "harsh" region — seen in Fig. 9, is consistent with a remark made in 1979 by Muller who noted that replacing a normal bridge with a solid blank (which would give $f_{\mathrm{rock}} \approx 8$ kHz) brought out the harsh and nasal characteristics of the violin compared with the standard bridge.[23]

Of course averaging over Δm tends to smooth out some

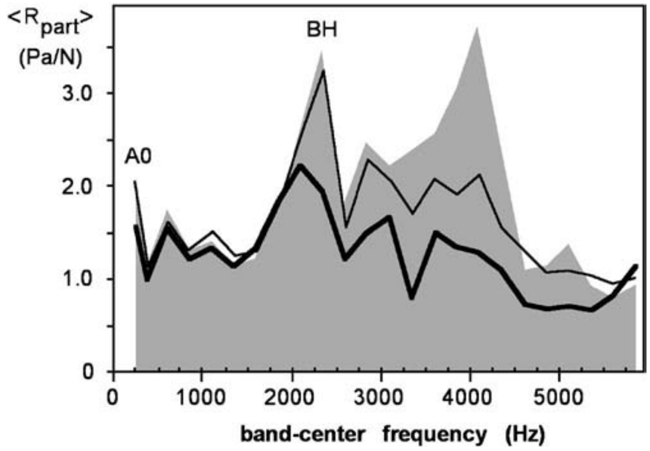

FIG. 10. Effect of varying $f_{\rm rock}$ from 3.4 kHz (shaded) to 3.0 kHz (thin curve) to 2.6 kHz (thick curve) on partial radiativity of the A. Guarneri 1660 violin.

of the $\langle R_{\rm part}\rangle$ variation attending $f_{\rm rock}$ changes. A closer look at the $\langle R_{\rm part}\rangle$ magnitude changes for just one bridge follows.

4. $f_{\rm rock}$ and $\langle R_{\rm part}\rangle$ — quality

The Oberlin 2005 experiment on the A. Guarneri violin narrowed the bridge waist rather more than considered safe for typical playing, stepping $f_{\rm rock}$ from 3.4 to 3.0 to 2.6 kHz, and added qualitative evaluations. This seemingly modest downward extension, which required removing only 2 mm (0.02 g!) from the bridge waist to drop $f_{\rm rock}$ from 3.0 to 2.6 kHz, changed the sound of the Guarneri from that of a good violin to a student (bad) violin! Since corpus normal modes showed no change in frequency, no change would be expected in mode shape or radiation efficiency, which is independent of mode amplitude. The important changes were in the relative mobility amplitudes for the various modes (and hence their radiativity) and consequent band averages. This experiment — where a minimal mechanical alteration not affecting the corpus created a large acoustic effect — provided an unambiguous example of how strong the filter action of the bridge is.

As might be expected from the qualitative evaluations the partial radiativity graph for the 2005 one-bridge experiment including the lowest $f_{\rm rock}$ data is very revealing (Fig. 10). A0 fell off ~25% as $f_{\rm rock}$ decreased from 3.4 to 2.6 kHz, with almost all of the change occurring in the 3.0–2.6 kHz transition. More striking was the overall falloff from 1.6 kHz upward, including the BH peak and 2800–4200 kHz in the “brilliant, clear” region. Relative to BH (averaged from ~1600 to 2600 Hz) both A0 and the 2800–4200 Hz regions fell off when $f_{\rm rock}$ dropped to 2.6 kHz.

Qualitative evaluations tracking the 3.4–3.0–2.6 kHz $f_{\rm rock}$ steps indicated certain consistent acoustic trends such as weaker, more uneven sound that did not carry as well, with the 3.0–2.6 kHz step being more noticeable. The measurements in Fig. 10 show significantly weaker overall partial radiativity at 2.6 kHz, with both 2.6 and 3.0 kHz showing noticeably weaker *relative* values in the 3000–4500 Hz band. Consistent with trends seen in the 2004 experiment (Fig. 8), $f_{\rm BH}$ dropped slightly. The overall acoustic profile also

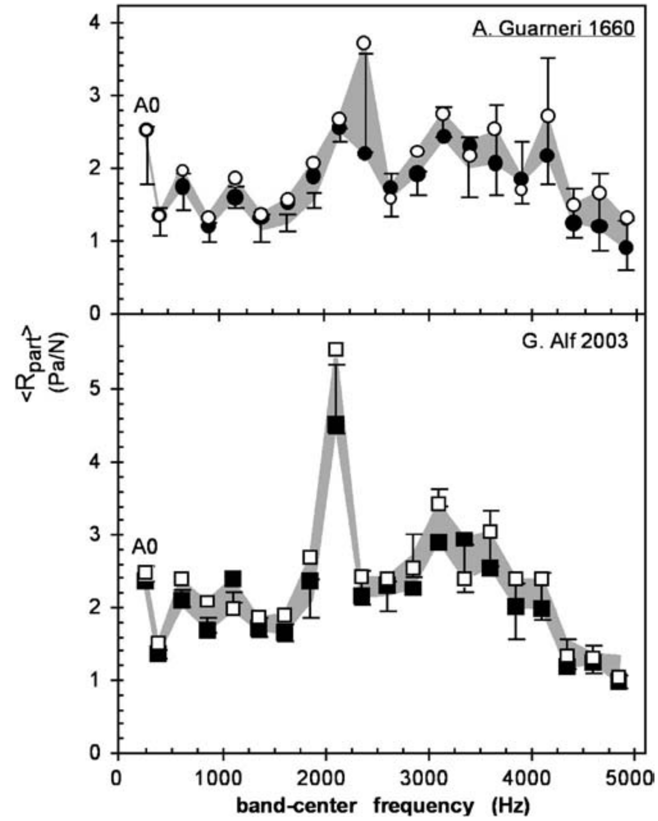

FIG. 11. Effect of decreasing wing mass (by 0.12 g in 0.04 g steps, averaged over $f_{\rm rock}$) on averaged partial radiativity for four bridges on old Italian (top) and modern violin (bottom). Closed symbols — $\Delta m=0$, open — $\Delta m=0.12$ g; shaded area min-max, all Δm. 1 s.d. errors for $\Delta m=0.04$ mass decrement average only (no curve).

changed dramatically: at 3.4 kHz the radiativity generally increased up to ~4000 Hz and then fell rapidly, whereas at 2.6 kHz the profile showed a general overall decrease. Such large acoustic profile changes clearly show the importance of waist trims to violin sound.

5. Wing mass decrements

By averaging across $f_{\rm rock}$ rows in the data matrix, the generalized effects of wing mass decrements on $\langle R_{\rm part}\rangle$ were extracted. So that a real Δm effect does not get buried by a possible change-of-wood effect, even though these bridges were matched closely, only the trend between $\Delta m(\rm g)=0$ and 0.12 will be discussed. In Fig. 11 the Δm partial radiativity data are presented, again following the format of Fig. 9.

From the min-max curve, where approximately 85% of the bands have their highest radiativity associated with $\Delta m=0.12$ g and approximately 75% their lowest with $\Delta m=0$, we infer that generally the largest mass decrement led to higher overall radiativity. If lower mass bridge tops lead to higher radiativity, then conversely adding mass to the violin bridge top — as in a violin mute — should lead to lower radiativity, which is consistent with experience.

At $f>f_{\rm BH}$ the Δm min-max band was not so wide overall as for $f_{\rm rock}$ in Fig. 9, but appeared slightly wider at $f<f_{\rm BH}$. One significant exception was for A0, which did not change significantly with wing mass decrements. The Guarn-

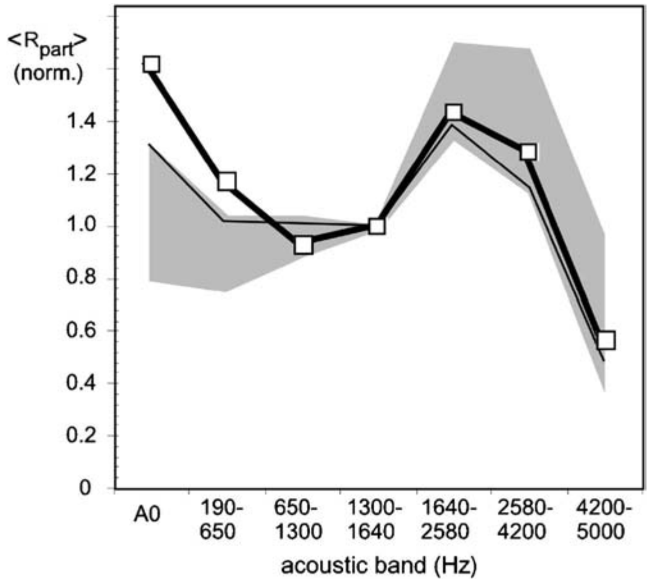

FIG. 12. Acoustic profiles for 20 Alf violin bridge trims, compared to "target" A. Guarneri profile (−□−). (Closest to target - thin line; shaded area denotes min-max region, all profiles normalized to 1300–1640 Hz band).

eri BH region was more sensitive to mass decrements than the Alf violin, similar to behavior seen for f_{rock} variations.

6. Acoustic profiling

Our measurements again confirm that old Italian violins are not necessarily louder (= higher radiativity when no perceptual complications are present) across the board than modern instruments, although in specific cases, for specific violins or specific regions they may well be (e.g., see Table IV, Ref. 24). Of most interest here is the question unintentionally posed by the wide range of f_{rock} and wing mass decrement modifications in the Oberlin experiments. Can an old Italian violin acoustic profile be matched by any one (or more) of the 20 separate modern Alf violin acoustic profiles (bridge modifications only!)?

To test this one A. Guarneri acoustic profile was chosen as the "target" — viz., the f_{rock}=3.0 kHz, Δm=0 acoustic profile. Is this the "best" choice? In our context it does not really matter. The playing tests in the Oberlin 2005 experiment were consistent with it being a good violin, while dropping to f_{rock}=2.6 kHz turned it into a bad violin. More to the point of this heuristic example is that any "exceptional" (= testers' preferred) violin could be measured in the apparatus and its acoustic profile used as the target for bridge modifications on any other violin to reach. (The aforementioned simplified bands 190–650, 650–1300, 1300–4200, 4200–6400 kHz (plus A0 separated out) will be used again, but note that measurements extended only to 5000 Hz, hence this latter band will cover only 4200–5000 Hz.)

Since the region near 1.5 kHz was insensitive to both f_{rock} and Δm variations (see Figs. 9–11) the 1300–1640 Hz band was chosen for normalization purposes for all curves across all measurements for the Alf and the target A. Guarneri curve. The normalized results are shown in Fig. 12. Out of 20 separate f_{rock}-Δm acoustic profiles only one Alf curve came close overall to the Guarneri curve, viz., the f_{rock} =3.6 kHz, Δm=0 curve. Commonly the acoustic profile would be similar below or above 1500 Hz, but not below *and* above. Qualitative tests were not performed in the 2004 measurement series so further remarks are not possible.

IV. CONCLUSIONS

The traditional view of the violin bridge being the string-to-corpus energy conduit was confirmed by modal and acoustical analysis results on 12 quality-rated violins.

The BH structure near 2.3 kHz for all violins was seen in the mobility spectra at every important point in the energy chain for every violin tested, good or bad, ultimately leading to a peak in radiativity; no significant good-bad radiation efficiency change was observed. Waist trims generally had little effect on BH frequency or magnitude. Our experimental scrutiny of the proposed relationship between BH driving point magnitude and violin quality provided no evidence to support this claim.

The complex motions of the bridge above 1.5 kHz and the minimal effect that varying f_{rock} had on f_{BH} confirmed the conclusion of Jansson and collaborators that the BH peak at the driving point arose not from isolated bridge motions at some rocking mode frequency, but rather from local corpus motions. These motions might be enhanced by the bridge. Relatively large f_{rock} changes creating only few-percent f_{BH} changes could be considered experimental evidence for the bridge substructure rocking behavior being subsumed into the overall violin response to excitation.

Bridge trims changed acoustic profiles significantly. The 3000–4200 kHz region was affected most strongly by f_{rock} changes, with decreases in f_{rock} accompanied by decreased radiativity. At the other end of the acoustic spectrum, A0 radiativity weakened substantially when f_{rock} dropped to its lowest values, especially 2.6 kHz — in addition to the above-noted falloff in the 3000–4200 Hz region. Falloff at both ends of the spectrum at the lowest f_{rock} values audibly diminished the sound quality of a violin, unambiguously demonstrating the filter properties of the bridge. Larger wing mass decrements generally increased radiativity, an anticipatable reversal of the effect of a violin mute.

Good-bad radiativity trends observed in the anechoic chamber and in the Oberlin 2005 partial radiativity experiment were similar. Good-bad differences in averaged-over-sphere violin radiativities were not seen in the BH magnitude or frequency, but rather in the relative strengths *below and above BH*: going from good to bad each had weaker A0/400–500 Hz and 3000–4200 Hz responses relative to BH. These partial radiativity changes were quite similar to f_{rock}-induced changes, especially the 3.0–2.6 kHz transition.

Perhaps a stronger argument can be made here. These experiments were *very* different: one compared different violins of different quality with different normal modes, while the other examined quality changes in the same violin arising from changes in the bridge's filter response, with no change in normal mode frequencies, shapes or radiation efficiencies, just relative mode magnitudes. Such similar good-bad acoustic trends for two such disparate experiments argues for greater generality than either alone.

There are some important additional implications. Broad-band acoustic profiles appear to offer the potential for directing violin sound quality to some definable goal. And given the comparatively more modest (and much more difficult to achieve) effects possible from modifying the violin vibration→radiation output filter, bridge shape and design modifications seem a more fruitful avenue to achieving good violin sound.

Finally, our results supporting and augmenting prior experiments and simulations signal an important transition in our understanding of the physical origin of the BH peak. It has evolved from the original notion of strong rocking motion of the bridge being transferred to the corpus into one where energy passing through the bridge sets the violin into vibration, and the bridge — no longer an isolated substructure —responds *as part of the violin* to corpus motions at the feet.

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