The effect of wood removal on bridge frequencies

O.E. Rodgers and T.R. Masino

University of Delaware. Newark. DE 19711. USA

SUMMARY

Finite element analysis methods have been used to calculate the effects of trimming bridges on the first several frequencies of vibration. Violin bridges and both standard and Belgian designs of cello bridges have been investigated. Calculations of both in-plane and out-of-plane vibrating modes have been made when the feet were rigidly fixed. In one case, no motion out-of-plane was permitted. In the other, only the string locations were restricted to in-plane motions. The analysis confirms and expands the previous concepts of bridge action. The density of modes above the fundamental mode appears to explain the action of the bridge in absorbing substantial amounts of energy at all frequencies above that of the lowest mode. The effects of trimming in different locations are different enough so that it would be possible for a violin maker to adjust individual frequencies.

INTRODUCTION

Bridges have long been known to be a critical and central element in the acoustical structure of violin family instruments. The current designs must represent a very long progression of experiments and refinements carried on by makers over the centuries. The efforts in recent decades by technical minds to understand the function of the bridge have been very well summarized by Cremer in his recent book on "The Physics of the Violin" [1]. The description given by Cremer for both violin and cello bridges is that of stiff structures which have two vibrating modes of interest, at which the bridges act as toned vibration absorbers. For the violin the frequencies of these modes are in the neighborhood of 3000 and 6000 Hz, for the cello, around 1000 and 3000 Hz.

The tuning of bridges, practiced for centuries by makers, has also been of interest to technical minds. Hacklinger has investigated (the effect of wood removal at various locations on a violin bridge mounted on a massive stiff surface and found that wood removal at various locations reduced the 3000 Hz frequency and changed the tone quality of test violins [2] [3]. Hutchins has summarized her experience in bridge tuning and the effects of wood removal at various locations and provided recommendations for tuning bridges [4].

Careful experimental work by Trott to measure energy transfer through the bridge of a violin into the body reveals that the bridge is acting as a significant energy absorber in a band of frequencies from roughly 3000 Hz to approximately 10,000 Hz [5]. This finding suggests that the violin bridge is playing a more complicated role than just being a tuned vibration absorber at 3000 Hz.

The senior author became interested in the bridge tuning technical problem after spending several months learning how to tune the bridge on a rebuilt violin which had a very acceptable tone except on the E string, where the sound was very "bright," "harsh," "tinny," and many other adjectives, depending on who was describing the tone. It quickly became apparent that there was plenty of advice from makers on how to alter the bridge to correct the situation. While all of the makers recommended removing wood in the flexible areas of the bridge, they differed widely in their recommendations on precisely where to cut and what the effect would be of wood removal at various locations.

The availability of a finite element program on a computer at the University of Delaware provided the incentive to study both violin and cello bridges to determine in detail the effects of wood removal at various locations on the natural frequencies of the bridges when they were mounted rigidly at their feet and when restrained, in addition, to vibrate only in the plane of the bridge. Both the standard cello bridge and the Belgian design cello bridge were investigated, because a colleague was interested in why some cello players preferred one over the other. When it became obvious that the density of the modes was too small to explain the energy absorption over a continuous band of frequencies, as observed by Trott, the calculations were extended to include out-of-plane modes with the feet fixed and preventing only the string locations from moving in the out-of-plane direction. A few incidental calculations have also been made of particular trimming patterns.

THE FINITE ELEMENT CALCULATION METHOD

It is now standard engineering practice to analyze complicated structures using the finite element method. The method consists of dividing the structure into discrete small pieces, describing these to the computer, and then asking the computer to solve the mathematical equations describing the deformation patterns by deforming the finite elements until they all fit together again under the imposed loading system. For vibration analyses the loading system is an inertial one that depends on the deflection of each of the elements in the structure. The analysis proceeds in an iterative style, attempting to solve the equivalent of several thousand simultaneous equations. Some shortcuts are taken in finite element vibration analysis because of the formidable computational task. The authors have used the finite element program SUPERB, developed by SDRC of Columbus, Ohio. Each element has been described as a solid element and the computer program solves the deformation equations without simplifications, i.e. variations in stresses and strains in all directions are permitted.

THE BRIDGES

All of the bridges were described to the computer in a fitted condition. The feet had been trimmed, the height cut down to an approximate height for a standard instrument, the top edge thinned to 1.4 mm for the violin bridge and 2.5 mm for the cello bridges, and the thickness tapered from the top to the full blank thickness at about the bottom of the heart region. The thicknesses of the legs and the feet were not changed from those of the blanks. The shapes are shown in Figure 1 for the violin and Figures 4 and 7 for the cello bridges.

The material properties used are shown in Table 1. These are typical of maple. The stiffest direction is the x direction.

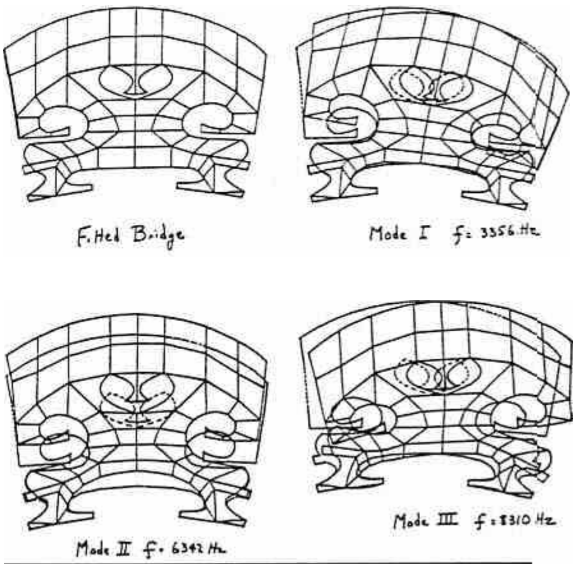

Figure 1. Violin bridge in-plane vibrating modes patterns before tuning.

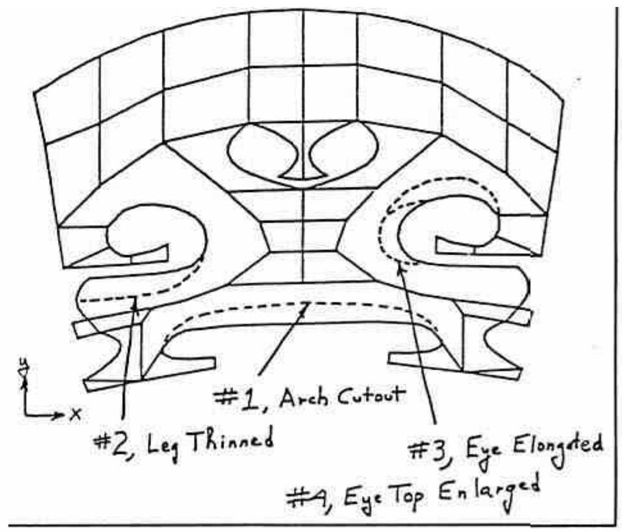

Figure 2. Cutout patterns for the violin bridge.

Table 1. Maple Wood Material Properties (Mega Pascals)

E_{xx}	10,000
E_{yy}	2,000
E_{zz}	1,200
G_{xy}	1,600
G_{xz}	1,600
G_{yz}	720
xy	.375
xz	.48
yz	.47
Density (g/cc)	.7

Table 2. Violin Bridge Frequencies when cutouts are applied.

Cutout Case	Frequencies (Hz)		
Mode	I	II	III
0. Fitted Bridge	3356	6342	8310
1. Cutout #1	3204	6000	7432
2. Cutouts #1 & #2	2915	5692	7322
3. Cutouts #1 & #3	2592	5453	7290
4. Cutouts #1 & #2 & #3	2289	5074	7206
5. Cutouts #1 & #3 & #4	2599	5538	7048
	(68%)	(81%)	(84%)
6. All Four Cutouts	2303	5159	6973

No changes in the stiffness properties have been made for assumed treatment during bridge manufacture to stiffen and harden the wood.

VIOLIN BRIDGE

Figure I shows the vibrating configurations and frequencies for the first three in-plane modes of the violin bridge. The dotted lines show the outline of the undeflected bridge position and the solid lines show the deflected shape. These are the primary modes of interest. The next pair of modes occurs at about 15000 Hz and represents motions of the wings in and out of phase. At about 20% higher frequency, there is a mode involving primarily the member in the center of the heart. Of particular interest is the third mode, which consists of a sideways motion and rotation of the middle section of the bridge, in which there is substantial motion at the string locations of a similar type to that of the first mode. This mode has not been detected in prior experimental studies of violin bridge vibration; even though its deflection configuration suggests that it should be excited by the vibrating string.

Figure 2 shows the cutout patterns which were investigated. In each cutout, 2 mm of wood was removed over most of the cutout and the ends blended into the bridge contour. Table 2 indicates the calculated frequencies when various combinations of the cutouts were applied. The most sensitive area for reducing modes 1 and 2 is cutout #3, which enlarges the eyes and reduces the width of the center flexible members. A 2 mm reduction on each side reduces mode I almost 20% and mode 2 about 9%. Increasing the arch between the legs has effect primarily on mode 3. Cutout #4, which decreases the stiffness of the elastic member between the heart and the eyes reduces mode 3 and increases the frequencies of modes 1 and 2.

Figure 3 shows the vibrating configurations of a bridge with all cutouts applied, Case 6. It can be seen that the vibrating configurations have not been changed by the removal of the indicated amount of wood. Case 6 represents an extreme case of bridge trimming. Consequently, a maker trimming a bridge does not have to be concerned that his work will change the nature of the bridge as a vibrating system.

Thus, the options now used by violin makers appear to make substantial reductions possible in all three bridge frequencies and offer ways to reduce frequencies selectively. It is no wonder that the advice received from makers was difficult to understand.

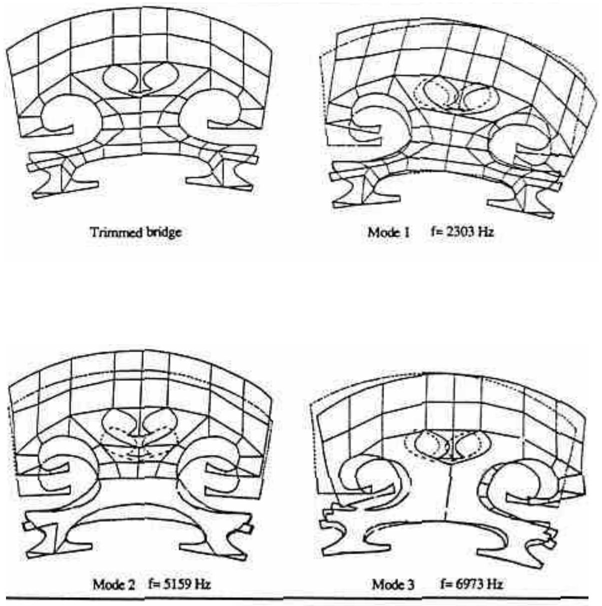

Figure 3. Violin bridge in-plane vibrating mode patterns, all locations trimmed.

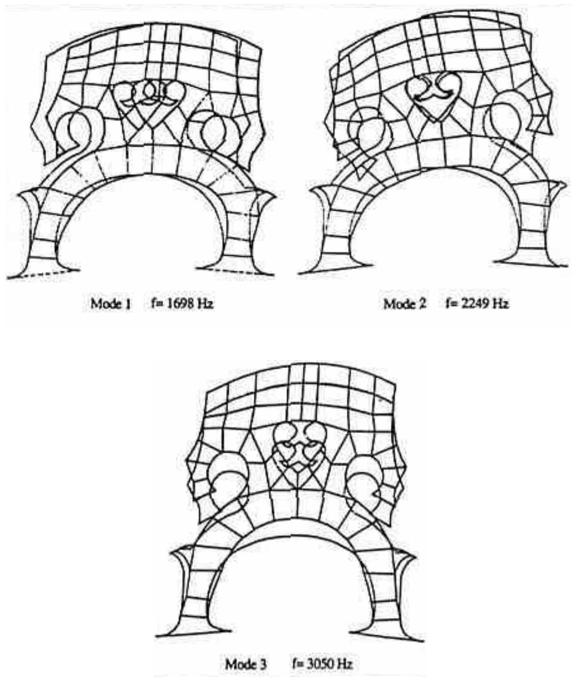

Figure 4. Standard cello bridge in-plane vibrating mode patterns.

STANDARD CELLO BRIDGE

Figure 4 shows the first three in-plane vibrating configurations of the standard cello bridge. The second and third modes are reversed as compared to the violin bridge. The frequency of the rotational mode is now lower than that of the mode in which the deflections are uniformly vertical. The next higher modes for this bridge also represent motions of details of the bridge. The two modes of the wings are at about 5500 Hz and the motion of the member in the heart occurs at about

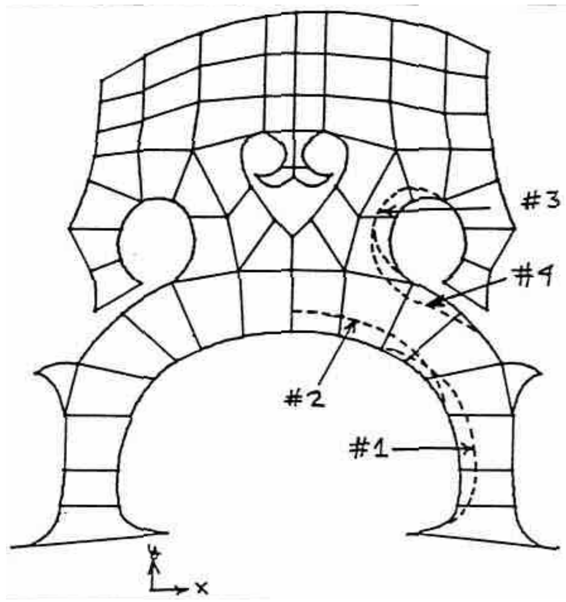

Figure 5. Cutout patterns for the standard cello bridge.

Table 3. Standard Cello Bridge Frequencies when cutouts are applied.

Cutout Case		Frequencies (Hz)		
	Mode	I	II	III
0. Fitted Bridge		1698	2249	3050
1. Cutout #1		1396	2093	2577
2. Cutout #2		1595	2002	2704
3. Cutouts #1 & #2		1345	1895	2470
4. Cutout #3		1575	2033	2987
5. Cutouts #3 & #4		1434	1937	2724
6. All Four Cutouts		1292	1428	2205

9000 Hz**.** In contrast to the violin bridge, most of the flexibility is in the legs. In Mode I, the motion is not a rocking and rotation but is, instead, almost entirely a horizontal translation of the upper portion of the bridge. The rocking motion occurs in the second mode. In mode 3 almost all of the deformation takes place in the legs.

Figure 5 shows the cutout patterns which were calculated for the standard cello bridge. For both cello bridges a 3 mm depth of cut was used. While the diagram shows only one side, all cutouts were applied symmetrically to both sides. Table 3 shows the frequencies when various cutout patterns were applied. The cutout at the upper portion of the legs is much less effective in changing mode 1 but a little more effective in changing the rotational mode than the cutout of the lower legs. Cutout #3 of the upper flexible members is not very effective in reducing the vertical translation mode. Once again, by proper choice of trimming location one can adjust individual bridge frequencies within some limits. A calculation of the case in which all cutouts were applied indicates, once again, that the cutouts did not change the configurations of vibrating bridge.

BELGIAN CELLO BRIDGE

Figure 6 shows the vibrating configurations for the first three modes of vibration. It should be noted that frequency of mode 1 is lower than that of the standard cello bridge and that of mode 3 is higher. The configurations are much the same. Figure 7 shows the cutouts, patterned after those for the standard cello bridge. Table 4 lists the frequencies when various cutouts are applied. Cutout 1 of the lower legs is once again more effective in reducing modes 1 and 3 than the upper leg cutout. Cutout 3 has almost no effect on modes 1 and 3 but a large effect on the rotational mode. Cutout 4 has no effect on mode 1 but substantial effect on the other two. It appears that it would be easier to adjust single modes in this bridge design than in the standard cello bridge design.

LENGTHENING THE LEGS

Calculations were made of the effect on bridge frequencies if the long legs of the bridge blanks were retained by trimming the upper portions of the bridge blank club feet and removing additional material from the top of the bridge to keep the overall height the same. The effects were appreciable in the cello bridges where the club foot was quite thick. The same general pattern of frequencies continues to exist but the frequencies are lowered 18%, 4%, and *8%* respectively for the first three modes. In the violin bridge, the foot of the blank is less thick. Frequencies were lowered by 2%, 4% and 7% for the first three modes.

BRIDGES AS TUNED VIBRATION DAMPERS

One of the key functions of the bridge is to filter out undesirable high frequency vibrations that would be unpleasant to the player and the listener. Trott's curves of power loss versus frequency indicate as much as a 20 dB drop for three different instruments at all frequencies above about 2500 Hz when driven from the bridge in a direction parallel to the bridge top [5] (Figures 13 and 14). The onset of the reduction occurred in one instrument at about 1500 Hz and in the others at about 2000 Hz. Presumably these frequencies indicate the extent to which the violin bridges had been trimmed to achieve a desirable tone at high frequencies.

Trott's data indicate that a violin bridge is effective over a wide range of frequencies as a good energy absorber — much more uniformly than one would expect from a tuned absorber operating at only two or three frequencies over a 2 to 1 frequency range. This suggests that there must be other modes of vibration that are also absorbing energy. It is possible that the longitudinal motions of the strings at the bridge are great enough to excite out-of-plane bridge vibrating modes. In order to investigate the plausibility of energy absorption by out-of-plane modes, calculations were made in which the feet were rigidly fixed, as before, but motions out of plane were permitted except at the string locations on the top. Table 5 shows the frequencies of the additional modes that were found for all three bridges and their relation to the in-plane modes.

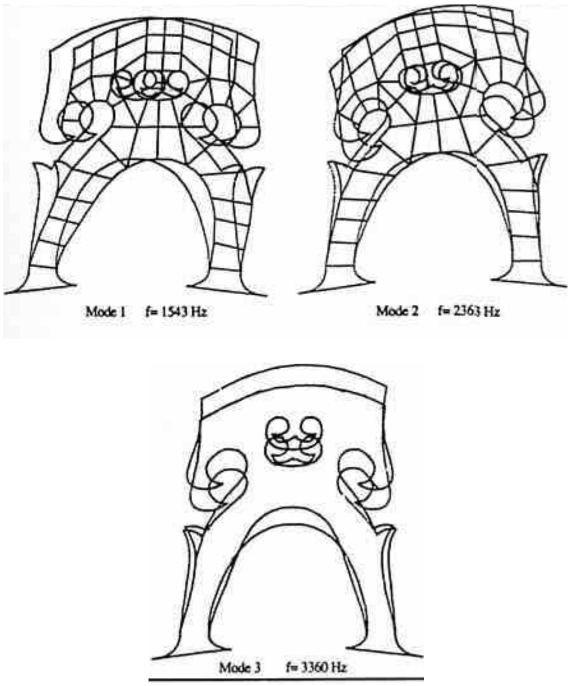

Figure 6. Belgian cello bridge in-plane vibrating mode patterns.

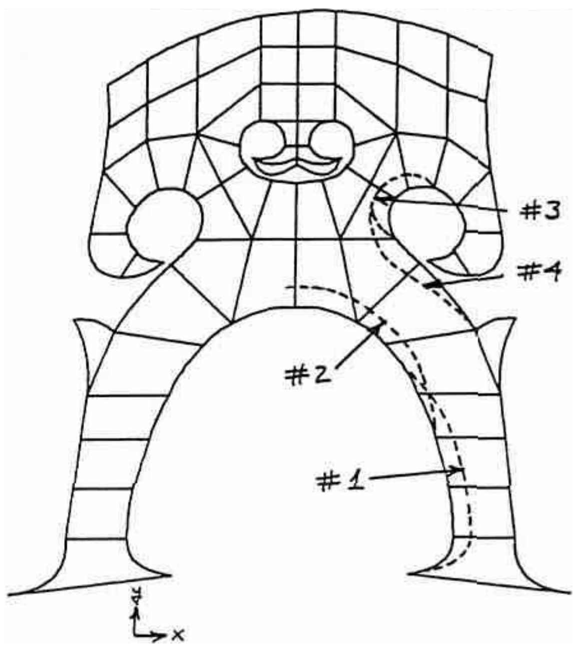

Figure 7. Cutout patterns for the Belgian cello bridge.

Table 4. Belgian Cello Bridge Frequencies when cutouts are applied.

Cutout Case		Frequencies (Hz)		
	Mode	I	II	III
0. Fitted Bridge		1543	2363	3360
1. Cutout #1		1290	2242	2909
2. Cutout #2		1374	2210	3182
3. Cutouts #1 & #2		1166	2095	2762
4. Cutout #3		1542	2104	3324
5. Cutouts #3 & #4		1523	1869	3133
6. All Four Cutouts		1189	1569	2508

Table 5. Bridge Frequencies (Hz), both in-plane and out-of-plane modes.

	In-plane	Out-of-plane
Violin	3353	
		3579
		4723
	6322	
		7462
	8445	
Standard Cello		
		1325
	1697	
		2152
	2271	
	3060	
		3665
		4755
Belgian Cello		
		1304
	1549	
		2356
	2383	
	3378	
		4263
		5070
		5436

Table 6. Bridge Frequencies (Hz), both in-plane and out-of-plane modes, with all cutouts applied.

	In-plane	Out-of-plane
Violin	2305	
		2907
		3584
	5206	
		6206
	7041	
Standard Cello		
		1184
	1294	
	1434	
		1848
	2218	
		3049
		4472
		4683
		4957
Belgian Cello		
		1167
	1196	
	1572	
		2094
	2529	
		3476
		4272
		5081
		5948

Figure 8 shows the vibrating configurations. In the lowest mode for both cello and violin bridges the center of the bridge moves out of plane. In the next mode, the middle section of the bridge rotates relative to each end. In the violin bridge, the third mode is one in which the center section assumes a dish shape with the outer portions moving one way and the center portion the other. There are also higher modes in the cello bridge* in which various leg configurations appear.

Table 6 lists the frequencies for in-plane and out-of-plane modes when all of the cutouts have been applied. There have been some shifts in relative position and, in the cello case, the frequencies of two modes may almost coincide. Is it possible that such a bridge might produce a wolf effect at a high frequency?

It is plausible to assume that the string can excite these out-of-plane modes to some extent, and the positions of the out-of-plane mode frequencies relative to the in-plane mode frequencies is such that a substantial amount of energy could be absorbed above the first frequency at which the bridge becomes an classic vibrating component of the violin.

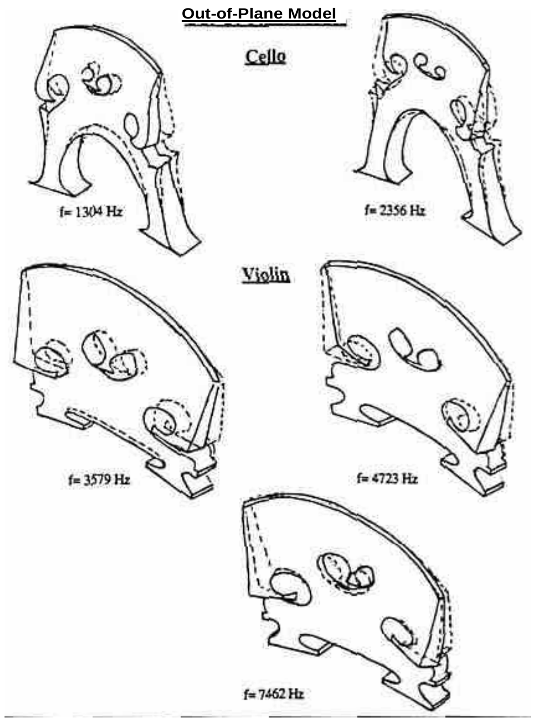

Figure 8. Out-of-plane vibrating mode patterns for all bridges.

CONCLUSIONS

Bridge trimming is obviously a very complex and powerful practice to adjust the overall sound of *a* violin type stringed instrument to have a desired mix of overtones. The examples of trimming that have been presented should provide a thoughtful violin maker with significant clues to guide his efforts to compensate by bridge trimming for any undesirable high frequency overtones in the basic instrument.

The computer detailed inputs still exist in the University of Delaware computer and can be used to calculate additional cutout schemes that have been found to be effective in bridge tuning. The senior author would like to hear about any such schemes and would be willing to calculate their effects on frequencies for comparison with the cutout patterns that have been described.

ACKNOWLEDGMENTS

The authors would like to thank the University of Delaware for access to the computing equipment and for support through an Engineering Scholar award.

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