Sound Production by a Vibrating Piano Soundboard: Experiment

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Abstract

The generation of sound by a piano soundboard is investigated experimentally, through measurements of the sound pressure, p, and the soundboard velocity, v_b, produced in response to a force applied at the bridge. Results for the ratio p/v_b as a function of frequency, for forces applied perpendicular to the soundboard at different locations (i.e., driving points) on the bridge, are presented. At all locations, p/v_b is largest at frequencies of order ~ 1 kHz, and falls off below a few hundred Hz and above ~ 5 kHz. A few results obtained with the force applied along the string direction (i.e., parallel to the plane of the soundboard) are also described. These results are compared and contrasted with previous experiments, and with theoretical expectations.

I. INTRODUCTION AND BACKGROUND

Pianos have been the subject of many experimental and theoretical investigations [1,2]. Much of this work has been concerned with string vibrations, the hammer string interaction, and of course, the spectrum of a piano tone and its variation with time. Relatively little attention has been paid to soundboard vibrations and how these produce sound.

A convenient way to characterize sound production by a vibrating soundboard is the ratio p/v_b, where p is the sound pressure and v is the velocity of the soundboard. Of course, both p and v_b will depend on the position at which they are measured, and on where the force is applied. It is perhaps most informative to apply the driving force to the bridge, since this is where the force from a string is applied. It is then natural to measure v_b at the same point on the bridge. As for p, while its magnitude will certainly vary with position, this will presumably not greatly affect the general variation of p/v_b with frequency.

So far as we know, there have been only two experimental investigations of p/v_b. Wogram [3,4] studied this quantity for an upright piano. He reported that it exhibits a maximum at a frequency near or below 1 kHz, and that it falls sharply at frequencies below about 100 Hz, and above about 1 kHz. In particular, he found that it falls by typically a factor of 10 as the frequency is varied from 1 to 5 kHz. In later experiments, Suzuki [5] investigated the integrated (with respect to area above the soundboard) sound produced by a grand piano. While he did not show results over a wide frequency range for any one location of either the driving force or measurement area, his results imply that integrated sound intensity normalized by the input power is approximately constant from 200 Hz up to 5 kHz. Hence, these two experiments, even though they measure slightly different quantities, do not appear to agree. One motivation for the present experiment was to resolve this discrepancy. Another was to provide systematic results for p/v_b for a representative choice of driving points. Such results are central for our ongoing effort [6] to construct a full, numerical model of piano sound production. Our intent is to use the new experimental results for p/v_b reported in this paper to guide and test numerical models of soundboard vibrations and sound production which are now under development.

In this paper we report studies of p/v_b using two techniques. One involved a "frequency domain" measurement, similar to that used previously [3,5], in which a force was applied to the soundboard using a shaker. The other method was a "time domain" approach, in which the force from a vibrating string was employed. Results obtained with these two methods are in agreement, and they are consistent with the those reported by Suzuki.

For most of our measurements the force was applied perpendicular to the plane of the soundboard. However, we also investigated the sound produced by a force parallel to the string direction. The aim here was to better understand how longitudinal string vibrations [2,7] give rise to sound.

II. EXPERIMENTAL SETUP

The experiments were carried out with two soundboards. One was in an intact (fully assembled) piano [8], while the other had been removed from an instrument [9] (both of the pianos were upright models). We will refer to the latter as the "free-standing" soundboard. However, its edges were attached to rigid metal braces, using closely spaced ($\approx$10 cm) screws. The intent was to approximate the boundary conditions found in an assembled piano. The bridge motion was measured with miniature accelerometers [10] attached with either a screw mounting or with wax. In previous work [11] we have established that both mounting schemes are satisfactory in the frequency range studied here. The sound pressure was measured using a microphone [12] positioned 30 cm from the center of the back of the soundboard. The results for other microphone positions were explored (as discussed some below), and the results at this position were representative. The measurements were performed in an ordinary laboratory, with no special acoustical material on the walls or ceiling. The acoustic environment was somewhat (but in our subjective opinion, not excessively) "livelier" than might be found in a living room. We do not believe that the measurements were sufficiently sensitive for this to have a significant effect.

Two different measurement schemes were employed. (1) A sinusoidal force was applied to the bridge using a shaker [13], with the accelerometer located as close as possible (typically within 1 cm) to the point where the force was applied. The rms acceleration and sound pressure were then recorded as the frequency was swept over the desired range. This type of measurement was most convenient with the free-standing soundboard, since all locations on both the treble and bass bridges were readily accessible. For the intact piano, only a limited region on the treble bridge was accessible, so it was not possible to study in this way the behavior for driving points on the bridge above the note G3 ($\sim$ 192 Hz). (2) We also measured p/v_b using the force from the strings to drive the soundboard. In this approach we recorded the accelerometer and microphone signals as functions of time just after a key was struck. These signals were then Fourier analyzed to obtain the relative strengths at the frequencies of the various partials. The ratio p/v_b at these frequencies could then be derived. While this approach only allows one to measure p/v_b at selected frequencies, these are the frequencies of most interest.

III. RESULTS

A. Swept Frequency Measurements

Figure 1 shows results for p/v_b for the free standing soundboard with the force applied at the bridge point for middle C. (Note: in order to make comparisons easiest, we have used similar scales for the axes in Figs. 1-3, 5, 7, and 8. In addition, the arbitrary units for p/v_b are the same in all of these figures, so that the values of p/v_b may be compared directly.) These results, which are representative for notes on the treble bridge, exhibit several features. (1) There are rapid fluctuations of p/v_b with frequency. Fluctuations of order a factor of ± 3 are common, even for changes in frequency much less than the spacing between different partials, which in this case is $\sim$ 262 Hz [14]. It is tempting to attribute these fluctuations to variations of the mechanical impedance, Z, of the soundboard as one moves from one vibrational mode to another [11]. Since the driving force in our experiments, F, varied smoothly with frequency (this was known from previous experiments with the same shaker [11]), fluctuations in Z will cause corresponding fluctuations in $v_b \equiv F/Z$. However, the results in Fig. 1 are for the ratio p/v_b, so the effect of fluctuations in v_b alone are removed. Hence, the fluctuations seen in Fig. 1 are not due simply (or solely) to fluctuations of the mechanical impedance. They are due instead to "modal" effects. That is, the various soundboard normal modes will have nodal lines at different locations. As the frequency is varied, the positions of the nodal lines will vary with respect to the driving point, and this will affect v_b. In addition, different modes will radiate with different directionalities, and this will affect p. We will return to these points below. (2) The "average" value of p/v_b, illustrated qualitatively by the heavy solid line in Fig. 1, exhibits slow fluctuations, which are of order $\sim \pm 2$. The largest values of p/v_b are found near 1 kHz, and the "average" value begins to fall substantially only above about 5 kHz.

This behavior is very different from that described by Wogram, who reported that the average value (in the sense just defined) of p/v_b falls by a factor of 10 or more in going from 1 kHz to 5 kHz. The reason for this discrepancy is probably linked to difficulties in his measurement of v_b, as has been discussed elsewhere [11,15]. Our results are quite consistent with the related measurements of Suzuki.

Figure 2 shows the results when the force is applied, and v_b is measured, at the bridge point corresponding to the note C6 (fundamental $\sim$ 1048 Hz). The major difference between this result and the behavior at C4, is that p/v_b begins its low frequency fall-off at approximately 300 Hz, which is about a factor of 2 higher than is the case for C4. Note that we again observe sizable fluctuations in p/v_b, whose magnitude is similar to that seen at C4. The behavior is basically similar for forces applied to the bass bridge, Fig. 3, except that the fall-off at high frequencies begins somewhat sooner, here at about 3 kHz.

B. Fourier Transform Results for p/v_b

To investigate the behavior of our intact piano we employed the Fourier transform approach described briefly in section II. In our particular experiments, the accelerometer and microphone signals were recorded simultaneously at a sampling rate of 22.05 kHz. Typical examples are given in Fig. 4, which shows the sound pressure just after the onset of sound, and the bridge acceleration just after the transverse string displacement pulse reaches the bridge, for the note C4. Since the bridge point for this note was, as noted above, not accessible (due to the bass strings, along with the action), for this measurement the accelerometer was positioned on the back of the soundboard (directly opposite the location where this string crosses the bridge), rather than on the bridge. The horizontal arrows in the figure show the period of the fundamental, and it can be seen that the high order partials of both signals are quite substantial.

These signals were Fourier analyzed to obtain the power spectra. For this calculation, 2048 digitized points were used, starting from the onset of the signal in Fig. 4. This corresponds to approximately 0.093 s of real time. Similar results for p/v_b were obtained if later portions of the signal were used instead (portions as late as 1 s after the onset were analyzed for comparison, and gave essentially identical results; the windowing used in the Fourier analysis was also found to not affect the results). We next normalized the acceleration spectrum by the square of the frequency, to obtain the velocity power spectrum. The values of the power for the different partials were then extracted, and the ratio of the pressure power spectrum to the velocity power spectrum, at the frequency of each partial, was obtained. This yielded $(p/v_b)^2$ at each of these frequencies.

Some results for p/v_b obtained from the signals in Fig. 4, and for several other measurements with the note C4, are shown in Fig. 5. These results show fluctuations in p/v_b as the frequency is varied from partial to partial, similar to what was observed above in the swept frequency measurements. To investigate the source of these fluctuations, data set (b) in Fig. 5 shows the effect of moving the accelerometer approximately 1 cm from its position in measurement (a). For both measurements the microphone position was kept fixed, approximately 40 cm from the back of the center of the soundboard, a location which placed it between two back posts. While moving the accelerometer this relatively small amount does change p/v_b somewhat, the major fluctuations, including the large dip near 1.5 kHz, are essentially unchanged. Result (c) in Fig. 5 shows the effect of moving the microphone 22 cm towards the bass end of the piano (it was again between posts). This is seen to have a much larger effect on p/v_b, and indicates that the fluctuations in p/v_b are due largely to the interference of sound emitted from different parts of the soundboard. This is not surprising, since the wavelength of sound at the fundamental is ~ 1.3 m, which is comparable to the soundboard (and other relevant) dimensions. The change found in moving the accelerometer a small amount (data sets (a) and (b) in Fig. 5), while smaller than the change found in moving the microphone, is also significant. We believe that it is due to the different amounts of sound generated by the different normal modes of the soundboard, together with the effect of their nodal lines on the value of v_b (as mentioned above). At any given frequency, several normal modes can be excited; these will have different sound generation efficiencies, and make contributions to v_b whose sizes vary with position on the board.

Figure 6 shows Fourier transform results for several different notes. In addition to the fluctuations noted in connection with the results for C4, two other features can be seen. First, the overall or "average" value of p/v_b is approximately constant over the range 500–5000 Hz. In considering the "average" behavior, we are attempting to separate the fluctuations (which have been discussed above) from the "overall" or background behavior (which we have attempted to indicate by the smooth curve). While this background behavior certainly does appear to vary somewhat over the range considered in Fig. 6, it varies by only about a factor of 2 or so over the range 500-5000 Hz. This is in sharp contrast to the results of [3], who reported that the background value of p/v_b fell by more than an order of magnitude in going from 1000 to 5000 Hz. Second, we observe from Fig. 6 that p/v_b falls somewhat below about 300 Hz. This is especially clear from the results for C3, and can also be seen for C4. These two features are consistent with the swept frequency results for the free standing soundboard, Figs. 1-3.

In order to more directly compare the two types of measurements, we show results for the note G3 for our intact piano in Fig. 7. The bridge position for this note was directly accessible, so here we were able to mount the accelerometer directly on the bridge. The force from the shaker was also applied to the bridge. Hence, in this case we can directly compare the two types of measurements (since the microphone and accelerometer positions were the same), although we have not attempted to determine the absolute magnitudes of p/v_b. The results here, as in the earlier figures, only give the relative values. Thus there is an undetermined overall scale factor for the two data sets in Fig. 7. To compare the two we have simply shifted the Fourier transform results by a constant factor (the dashed curve), and the results from the two rather different measurements are seen to be in fairly good agreement. An interesting difference is near 2000 Hz, where the Fourier transform results appear to be somewhat larger than the swept frequency measurements. This difference may simply be due to uncertainties in the Fourier transform results; at these high frequencies the Fourier amplitudes are quite small, making it difficult to extract accurate values of p/v_b. However, it is also possible that another effect is becoming important, and that effect is the subject of the next section.

IV. SOUND PRODUCTION BY AN IN-PLANE FORCE ON THE BRIDGE

It is well known that the blow of a piano hammer excites both transverse and longitudinal vibrations of the string [2,7]. The transverse vibration leads to a force on the bridge which is directed perpendicular to the soundboard, and thus to sound, and this sound generation has been the main subject of the present work. Longitudinal string vibrations will yield a force on the bridge which is along the string direction, i.e., parallel to the plane of the soundboard. This force will also drive soundboard vibrations which can produce sound, although one might expect that the amount of sound generated by this mechanism will be small. To the best of our knowledge, generation of sound via this mechanism has not previously been studied.

Longitudinal string forces might have an impact on our Fourier transform measurements for the following reason. This measurement uses the force from a string to drive the bridge. Since the string force will have components which are both perpendicular and parallel to the soundboard, this measurement will detect sound from both sources. This is in contrast to the shaker measurements, in which the force is applied (by the shaker) purely perpendicular to the soundboard. Indeed, one might now wonder why the two types of measurements should ever agree (as we have already observed above). One reason is that the longitudinal string vibrations have a much higher frequency than the transverse ones. The longitudinal wave speed is about an order of magnitude higher than the transverse speed [2,7], making the corresponding frequencies higher by the same factor. Experiments have shown that the longitudinal vibrations have most of their strength near 2–4 kHz, so the sound they produce would not interfere with most of the measurements presented above. However, they might be the cause of the small peak in p/v_b seen in the Fourier transform measurements in Fig. 7.

To investigate this question, we have used a shaker to apply a force along the string direction for the free-standing soundboard, and measured p/v_b for this configuration. Note that here v_b is the bridge velocity *along the string direction.* This measurement was performed by aligning the axis of the shaker along the string direction, and using a long (22 cm) stinger rod, so that the force could be applied at the top edge of the bridge, at the same point at which the force from the string would be applied. This is important, since such an in-plane force will exert a substantial torque on the bridge. Presumably, the resulting twisting motion of the bridge is the mechanism by which the soundboard is excited and sound is produced [16]. The accelerometer was oriented so as to detect motion parallel to the string direction, and was mounted on the edge of the bridge very close (within 1 cm) to where the stinger made contact. Some results are shown in Fig. 8. In all of our previous results in this paper we have considered the bridge velocity in the direction perpendicular to the plane of the soundboard. Here, however, we are considering v_b along the string direction, and in Fig. 8 we have plotted $p/v_b(parallel)$. We have also measured $v_b(perpendicular)$ as produced by a parallel force, and found that for a parallel force of the same size, these two velocities are *very* similar in magnitude at all frequencies studied. The reason why $v_b(parallel) \approx v_b(perpendicular)$ is not clear to us at present, but it does mean that the semi-quantitative behavior of p/v_b does not depend on which velocity component is considered.

Returning to Fig. 8, we see that the ratio $p/v_b(parallel)$ is largest near 3 kHz, which is also the frequency range where the longitudinal vibrations are largest [7]. It is also worthwhile to compare the $p/v_b(parallel)$ as measured here to $p/v_b(perpendicular)$ as found with the force applied perpendicular to the soundboard (Fig. 1). We find that under similar conditions, i.e., the same microphone location, for the bridge position for the (same) note C4, $p/v_b(perpendicular)$ measured with a perpendicular driving force is approximately *equal* to $p/v_b(parallel)$ measured with a driving force parallel to the string direction. That is, the "arbitrary units" used in Figs. 1 and 8 were the same, from which we see that near a frequency of 3 kHz, p/v_b was approximately the same in the two cases. This comparison is made difficult by the fluctuating nature of p/v_b, so there is perhaps a factor of 2 or 3 uncertainty involved. Nevertheless, we find that $p/v_b(parallel)$ is surprising large.

V. DISCUSSION

In this paper we have presented new results for the production of sound by a piano soundboard. The measurements were carried out with two different techniques, which yielded similar results for a free-standing soundboard and an intact piano. Our results are consistent with the earlier results of Suzuki [5], but are in sharp disagreement with those reported by Wogram [3,4].

Several features of our results can be readily understood, at least qualitatively. The fluctuations with frequency seem due largely due to interference effects, and are a strong function of the position of the microphone (i.e., the listener). These fluctuations can be quite substantial; for example, for the note G3 with our intact piano, p/v_b for the third partial can be nearly a factor of 10 larger than the first or second partial. We also find that p/v_b falls at low frequencies, a result that is probably caused the wavelength becoming larger than the size of the source.

We have also presented the first measurements of the sound produced by a force applied parallel to the string direction. In this case $p/v_b(parallel)$ is surprisingly large, implying that longitudinal string vibrations produce sound with a (relatively) high efficiency. This result should be essential in understanding the importance of longitudinal string vibrations in tone production.

To the best of our knowledge, there have not yet been any quantitative calculations to which we can compare our experimental results. In recent work with a simple numerical soundboard model [6], we calculated p/v_b using two extremely crude approximations. One of the results is actually consistent with the measurements we have reported here, but that agreement is likely accidental. A quantitative numerical calculation of the sound pressure in the vicinity of a vibrating soundboard seems feasible. We hope to report on such a calculation in the near future.

ACKNOWLEDGMENTS

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[7] See, for example, N. Giordano and A. J. Korty, "Motion of a Piano String: Longitudinal Vibrations and the Role of the Bridge," J. Acoust. Soc. Am. **100**, 3899 (1996).

[8] The piano was an upright made by the Charles Fredrich Stein Company in approximately 1935.

[9] The free-standing soundboard was taken from an Estey spinet piano.

[10] Two different accelerometers, both obtained from PCB Piezotronics, were used. One (model 352B68) had a mass of 2.0 g, while the other (model 352A10) had a mass of 0.7 g.

[11] N. Giordano, "Mechanical impedance of a piano soundboard," J. Acoust. Soc. Am. **103**,

2128 (1998).

[12] The microphone was a model 130A10 from The Modal Shop, Inc.

[13] The shaker was a model V102 from Ling Dynamical Systems.

[14] To accurately measure or characterize the magnitude such rapidly varying fluctuations, it is useful to be aware of the effective resolution in frequency. That is, the results for p/v_b are effectively averaged over a range of f; the use of a larger averaging interval in frequency can reduce the magnitude of the fluctuations in p/v_b. In order to facilitate comparisons, we used approximately the same frequency resolution in Figs. 1-3 and 7. This resolution varied smoothly from ~12 Hz at the lowest frequencies, to ~50 Hz near 1 kHz, to ~ 300 Hz at the highest frequencies. The frequency resolution was much wider for the measurements in Fig. 8 (as evidenced by the spacing between the data points), and was near 100 Hz at the lowest frequencies, and 300 Hz near 1 kHz. For this reason, the fluctuations appear smaller in Fig. 8.

[15] As discussed in Ref. [11], it appears that the magnitude of v_b was underestimated in Refs. [3] and [4], due to a mechanical decoupling of the accelerometer from the soundboard.

[16] A more complete discussion of this mechanism would require a measurement of the bridge velocity in the parallel direction produced by a measured parallel force; i.e., the corresponding mechanical impedance. We will report on such measurements in the near future. For the purposes of the present paper, where our emphasis is on p/v_b, impedance measurements are not required for the analysis.

FIGURES

FIG. 1. Results for p/v_b as a function of frequency for the free standing soundboard. The force was applied using the shaker at the point where the strings for the note C4 cross the bridge. The microphone was 30 cm from the center of the back of the soundboard. The heavy solid line here, and in the next two figures, is drawn as a guide to the eye, to emphasize the "average" behavior.

FIG. 2. Same as Fig. 1, but the force was applied at the bridge point for the note C6.

FIG. 3. Same as Fig. 1, but the force was applied at the bridge point for the note A2.

FIG. 4. Sound pressure (top) and bridge acceleration (bottom) just after the strings for the note C4 (middle C) were set into motion by a hammer blow. The horizontal arrows show the period of C4.

FIG. 5. Fourier transform results for p/v_b for the note C4 of our intact piano. The results labeled (a) were derived from the data in Fig. 4.

FIG. 6. Fourier transform results for p/v_b for several notes of our intact piano. The units on the vertical axis are arbitrary, and the results for each data set are displaced vertically for clarity.

FIG. 7. Fourier transform (dotted curve) and swept frequency (force applied with the shaker) results (solid curve) for p/v_b for the note G3 of our intact piano. The units on the vertical axis are arbitrary, and the results for the two data sets are displaced vertically for clarity. The dot-dashed curve shows the impulse results shifted so that they approximately overlap the swept frequency measurements.

FIG. 8. Results for $p/v_b(parallel)$ for the free-standing soundboard, obtained with the force applied parallel to the string direction. The smooth curve is a guide to the eye.

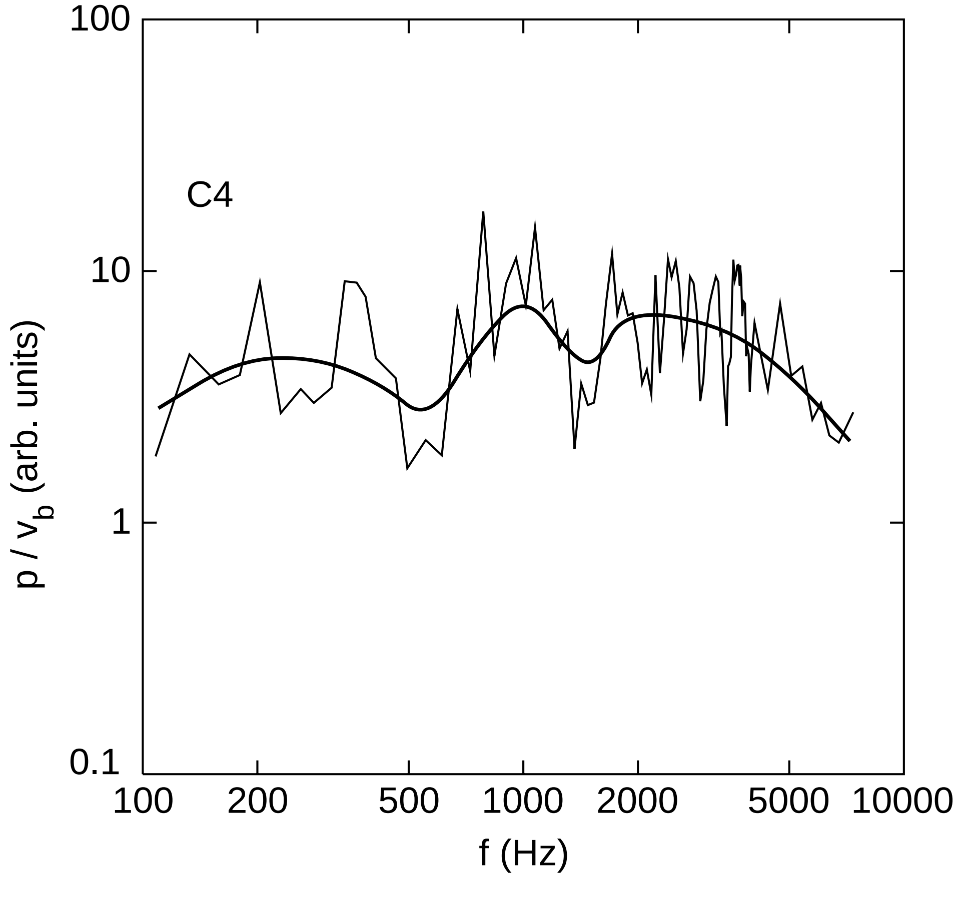
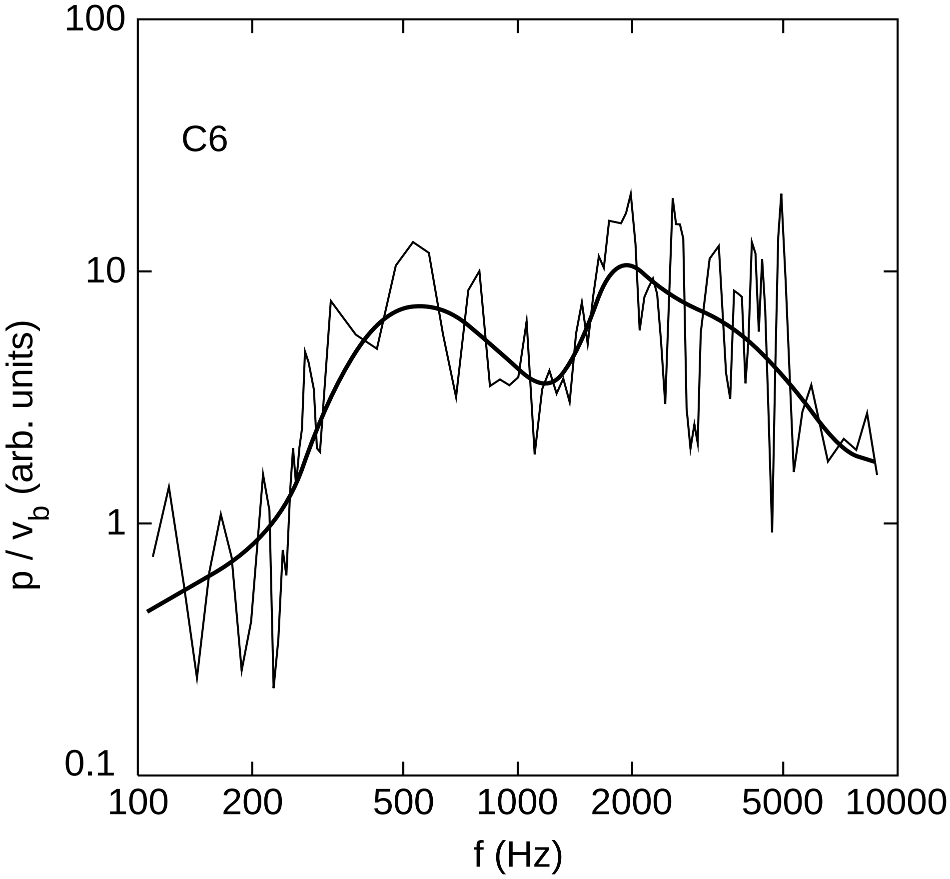

C4
100
10
1
0.1
100
200
500
1000
2000
5000
10000
f (Hz)
p / v$_b$ (arb. units)

Figure 1



100
10
1
0.1
C6
p / v_b (arb. units)
100
200
500
1000
2000
5000
10000
f (Hz)

Figure 2

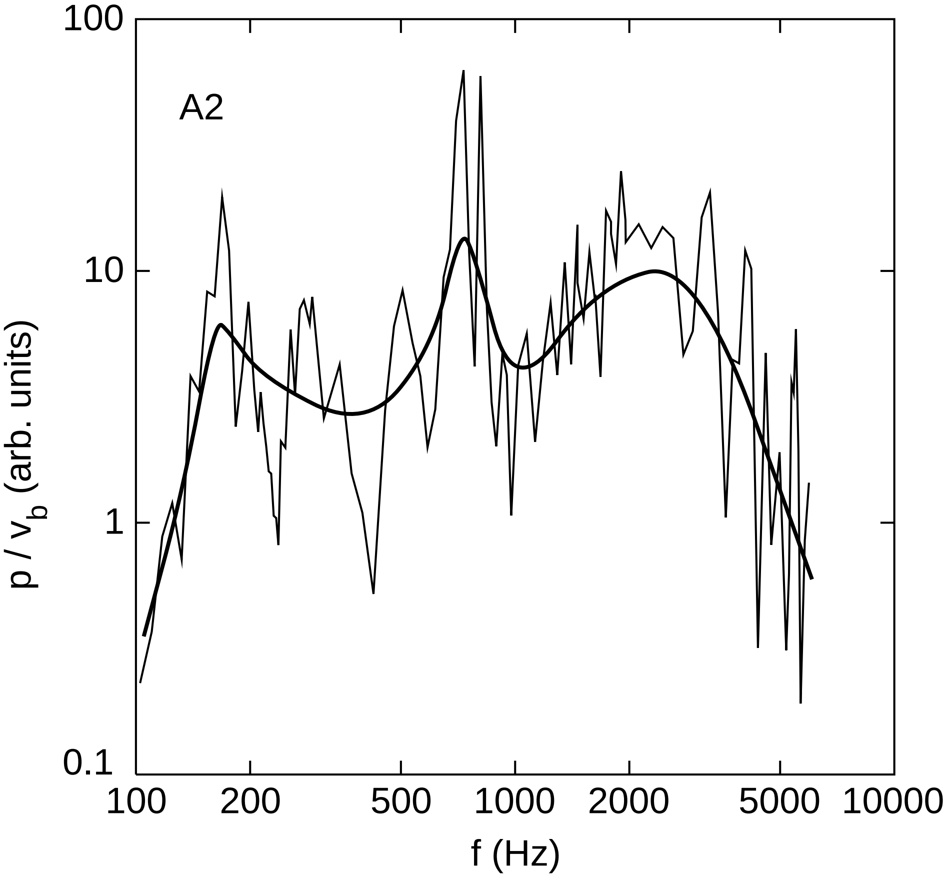

100
10
1
0.1
A2
p / v_b (arb. units)
100
200
500
1000
2000
5000
10000
f (Hz)

Figure 3

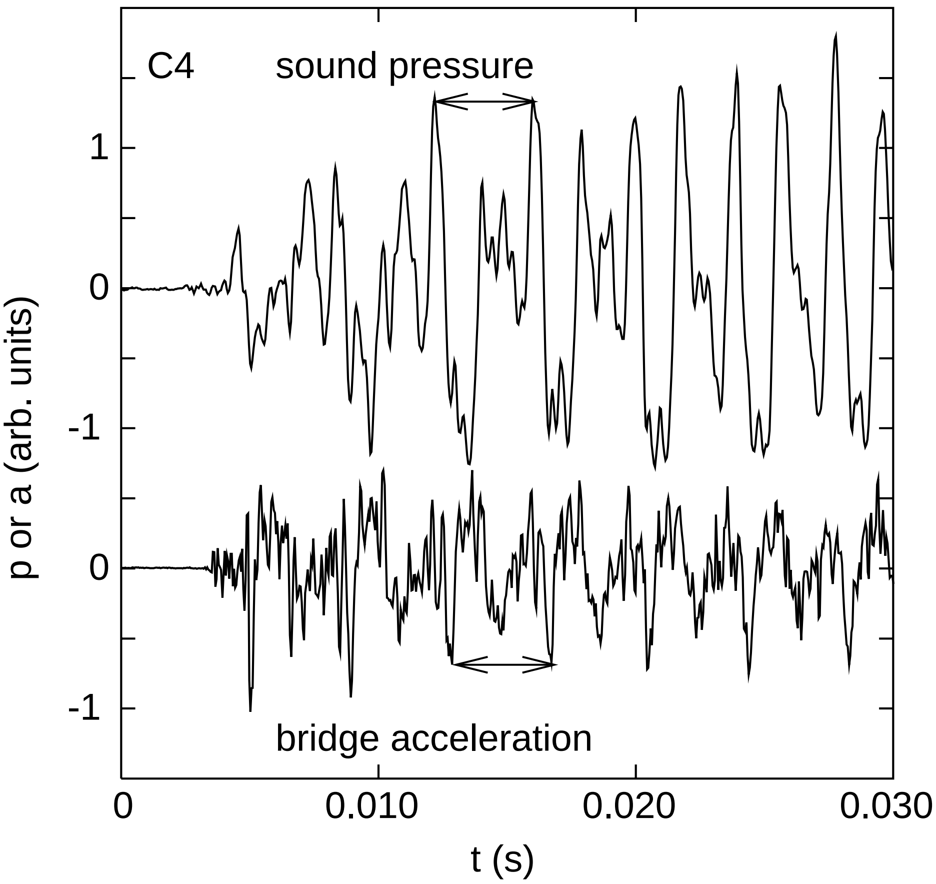
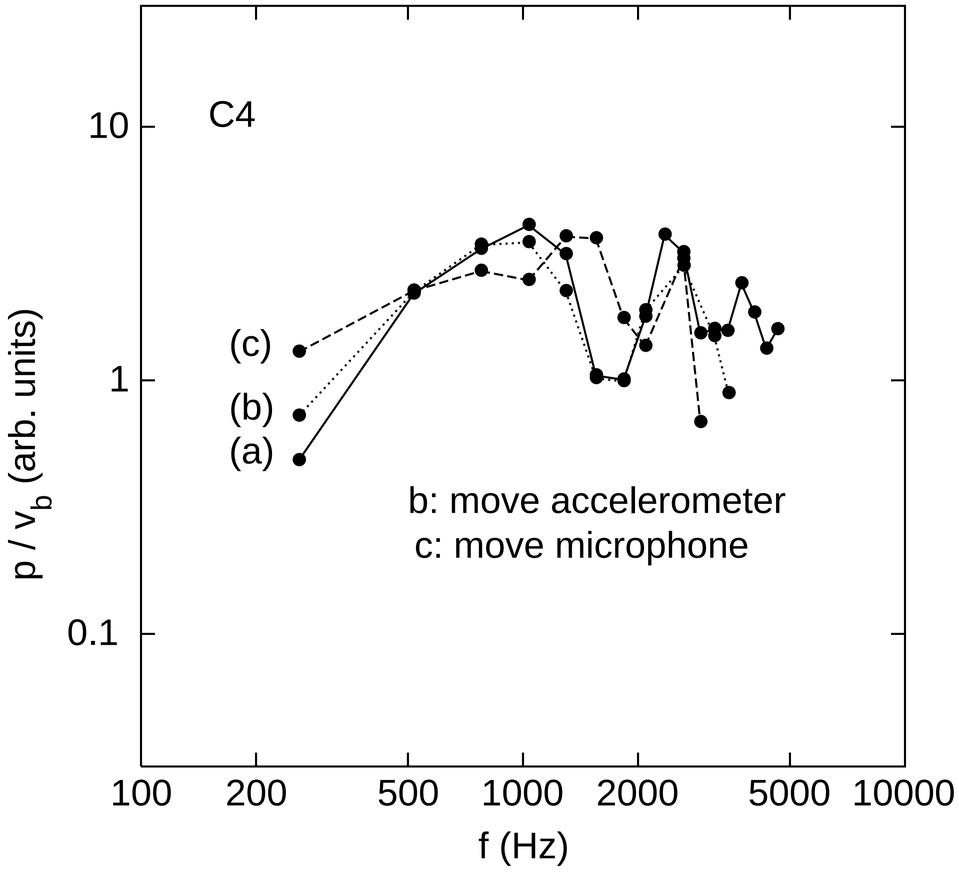
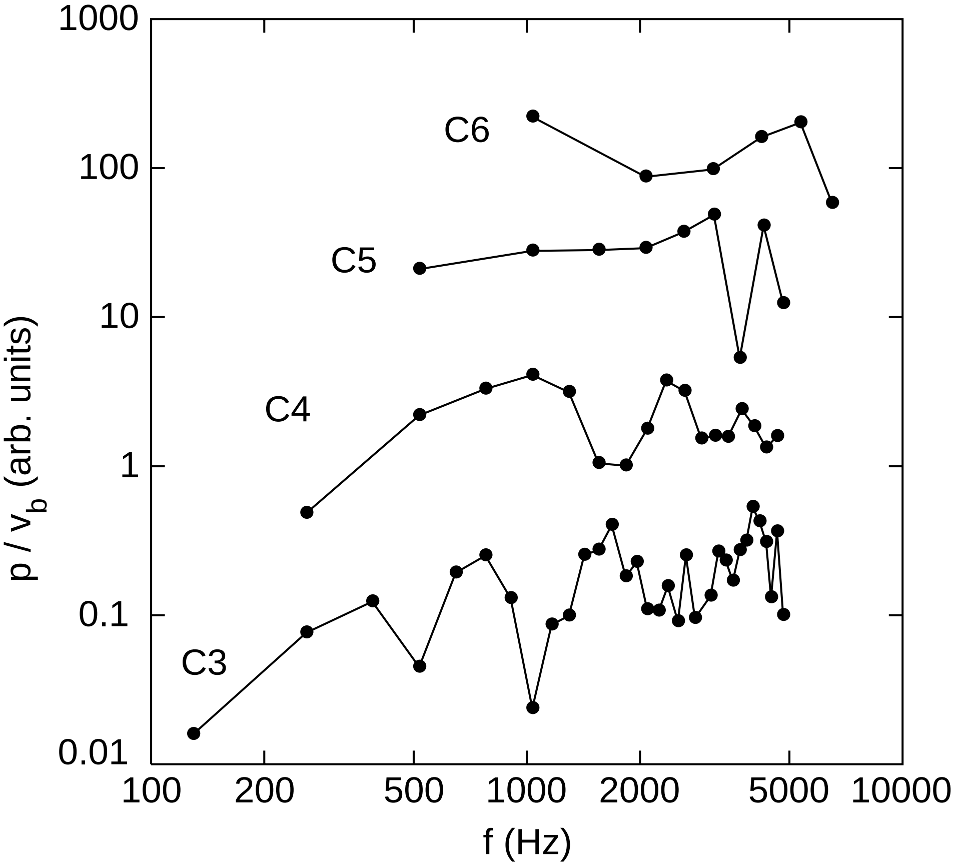

C4
sound pressure
bridge acceleration
1
0
-1
0
-1
p or a (arb. units)
0
0.010
0.020
0.030
t (s)

Figure 4



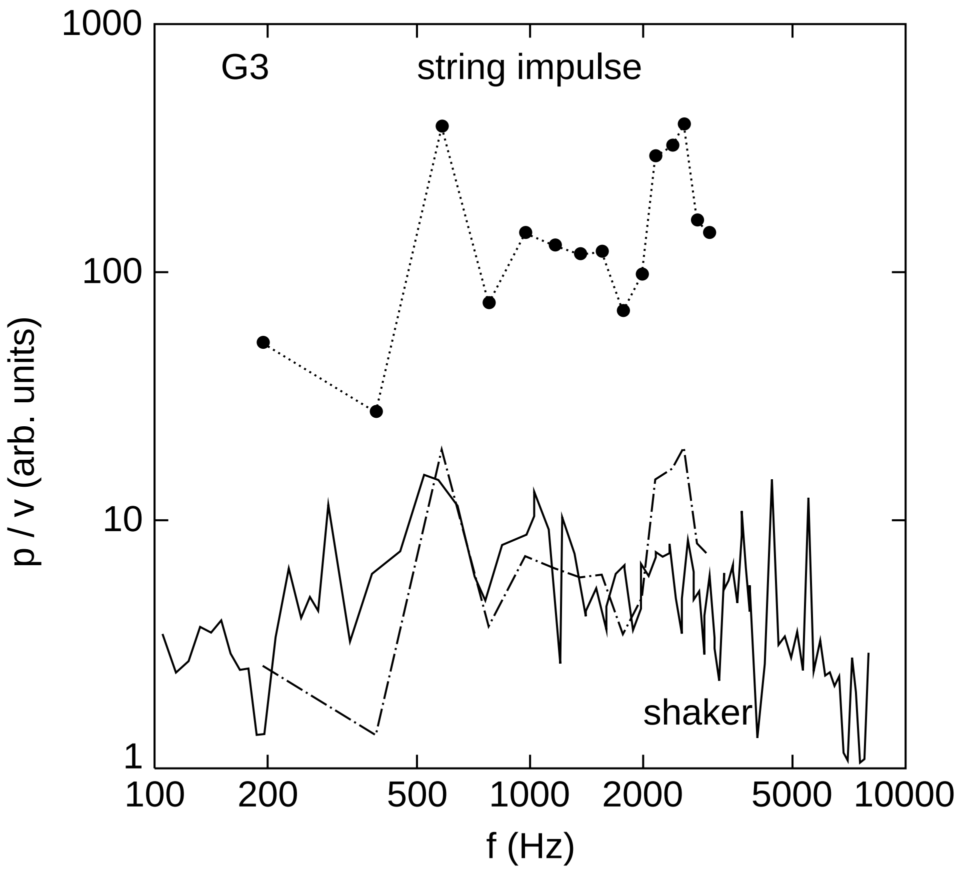
C4
10
1
0.1
(c)
(b)
(a)
b: move accelerometer
c: move microphone
p / v_b (arb. units)
100
200
500
1000
2000
5000
10000
f (Hz)

Figure 5



1000
100
10
1
0.1
0.01
100
200
500
1000
2000
5000
10000
f (Hz)
p / v_b (arb. units)
C6
C5
C4
C3

Figure 6



G3
string impulse
shaker
p / v (arb. units)
1000
100
10
1
100
200
500
1000
2000
5000
10000
f (Hz)

Figure 7

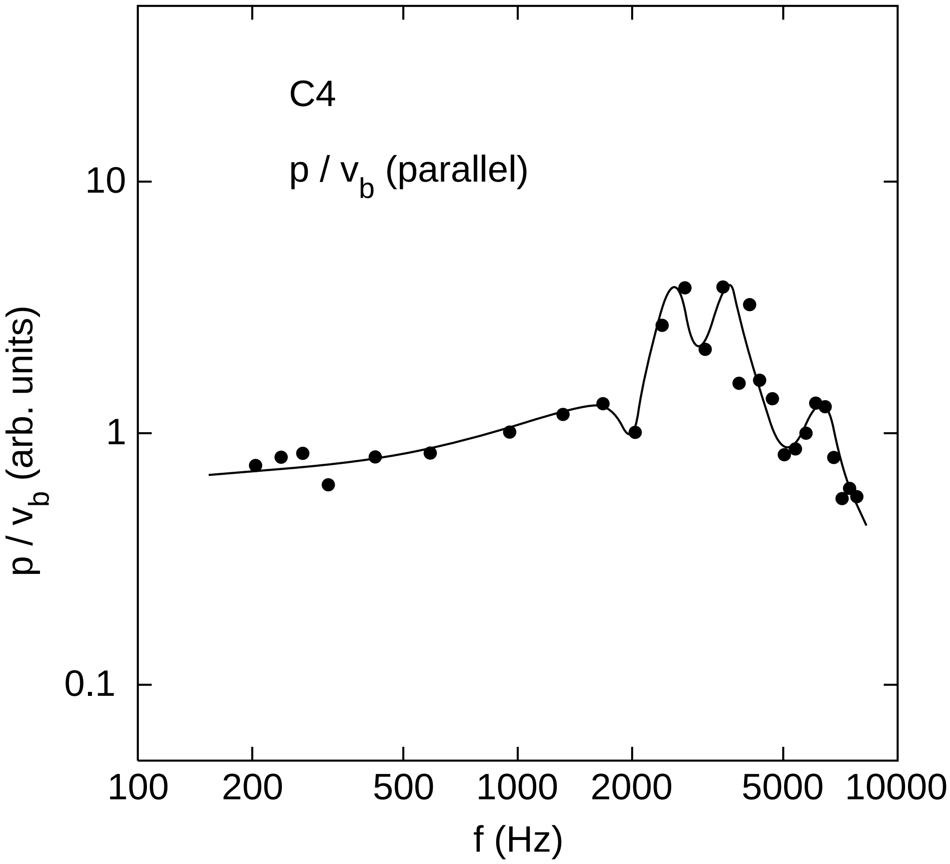

C4
p / v_b (parallel)
10
1
0.1
p / v_b (arb. units)
100
200
500
1000
2000
5000
10000
f (Hz)

Figure 8