Sound power and vibration levels for two different piano soundboards

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Sound power and vibration levels for two different piano soundboards

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Abstract. This paper compares the sound power and vibration levels for two different soundboards for upright pianos. One of them is made of laminated spruce and the other of solid spruce (tone-wood). These differ also in the number of ribs and manufacturing procedure. The methodology used is defined in two major steps: (i) acoustic power due to a unit force is obtained reciprocally by measuring the acceleration response of the piano soundboards when excited by acoustic waves in reverberant field; (ii) impact tests are adopted to measure driving point and spatially-averaged mean-square transfer mobility. The results show that, in the mid-high frequency range, the soundboard made of solid spruce has a greater vibrational and acoustic response than the laminated soundboard. The effect of string tension is also addressed, showing that is only relevant at low frequencies.

1. Introduction

In pianos the soundboard is a wooden panel reinforced by wooden beams. It is connected to the strings at the bridges and has the role of converting string vibration into sound. In manufacturing high quality pianos particular care is devoted to the selection and preparation of the wood. Typically soundboards are made of strips of solid spruce (tone-wood) joined together at the edges; however laminated or plywood panels are also commonly found, particularly in upright pianos [1].

When dealing with the piano soundboard most of the published research takes it into account as a component of a model of the whole sound generation process in the piano (see e.g. [2] and [3]). In this sense several results are now published about measurements and modelling of vibration of the soundboard [4][5][6]. Also sound pressure levels at various locations near the soundboard surface have been previously studied with the goal of correlating them to the vibration and/or to define the directivity of the piano soundboard ([7][8]). More related to the goal of this present study, Suzuki presented measurements results for radiated power and mechanical input power in a grand piano soundboard [9].

This study aims at proposing an engineering approach to assess the acoustic power and the average vibration levels of soundboards. Following this, a comparison is presented between a tone-wood soundboard and a laminated one. These soundboards also differ in the number of ribs and the manufacturing process. The measurement method allows the difference to be quantified, in terms of acoustic power, between soundboards believed to be of higher and lower quality.

The radiated acoustic power of the two soundboards due to a unit force is obtained using the reciprocity principle. The spatially averaged mobility is obtained by performing impact tests and measuring the vibration over the surfaces using a scanning laser vibrometer. The two soundboards are tested first with detuned and damped strings. For the tone-wood soundboard the effect of string tension is also addressed by repeating the measurements after tuning the strings to their normal pitch. The measurement range is between 100 and 5000 Hz.

2. Reciprocity theory

The reciprocity principle in acoustics was first applied by Lord Rayleigh [10], who stated that the acoustic pressure registered at a point 1, generated by an omnidirectional point source located at a point 2, is the same acoustic pressure registered at 2 if the same source were at 1. Reciprocity was extended to a vibroacoustic context by Lyamshev [11], who declared that the transfer function between a point force F exciting a linear vibrating structure at point A, and the sound pressure p produced at B by the vibration of that structure, is equal to the transfer function between the volume velocity Q of a point monopole source located at B, and the resulting vibration velocity v produced in the structure, at the same point A where the former excitation force was applied in the same direction. Figure 1 shows the reciprocity principle.

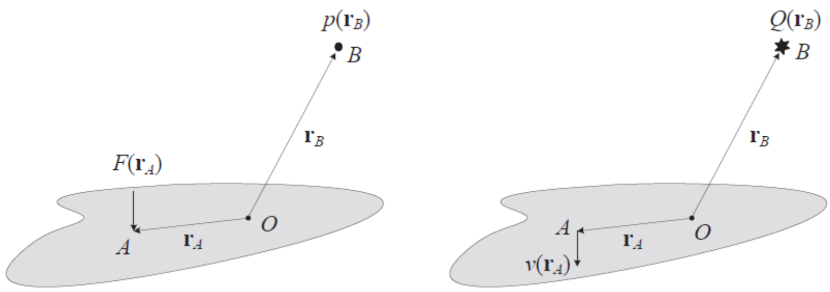


Figure 1. Direct force on the structure (left) and reciprocal excitation of the structure (right), from [12].

In terms of equations it can be written as

$$\frac{p(\overrightarrow{r_B})}{F(\overrightarrow{r_A})} = -\frac{v(\overrightarrow{r_A})}{Q(\overrightarrow{r_B})} \qquad (1)$$

where $\overrightarrow{r_B}$ and $\overrightarrow{r_A}$ are the position vectors in the medium and in the structure, respectively.

The measurement method adopted in this paper makes use of acoustic diffuse field properties, as fully described in [12]. In this case, the radiated sound power of the structure can be normalized by the mean-square force that excites the structure at point A, in order to give

$$\frac{W_{rad}}{\overline{F_A}^2} = \frac{S\overline{\alpha}\left\langle \overline{p^2} \right\rangle}{4\rho_0 c_0 \overline{F_A}^2} \qquad (2)$$

where $S\overline{\alpha}$ is the room absorption, $\left\langle \overline{p^2} \right\rangle$ is the spatially-averaged, mean-square pressure caused by the vibrating structure, and $\overline{F_A}^2$ is the mean square force applied at point A. Since in a diffuse field the sound pressure is approximately the same everywhere, Eq. (2) can be rewritten in terms of the sound pressure at point B

$$\frac{\overline{W_{rad}}}{\overline{F_A^{\ 2}}} = \frac{S\bar{\alpha}\overline{p_B^{\ 2}}}{4\rho_0 c_0 \overline{F_A^{\ 2}}} \tag{3}$$

Applying the reciprocity principle (Eq. (1)), Eq. (3) can be rewritten as:

$$\frac{\overline{W_{rad}}}{\overline{F_A^{\ 2}}} = \frac{S\bar{\alpha}\overline{v_Q^{\ 2}}}{4\rho_0 c_0 \overline{Q^2}} \tag{4}$$

where $\overline{v_Q^{\ 2}}$ is the mean-square velocity of the structure at point A caused by the acoustic excitation generated by a point monopole source having a mean-square volume velocity $\overline{Q^2}$, located at point B. Moreover, the source volume velocity Q can be obtained by performing sound power measurements. The radiated sound power of a compact source is given by:

$$W_Q = \rho_0 c_0 \overline{Q^2} \frac{k^2}{4\pi} \tag{5}$$

where k is the acoustic wavenumber. The sound power of a source in a reverberant field can be obtained from the mean-square pressure $\left\langle \overline{p_Q^{\ 2}} \right\rangle$ produced by the source with volume velocity Q as

$$W_Q = \frac{S\bar{\alpha}\left\langle \overline{p_Q^{\ 2}} \right\rangle}{4\rho_0 c_0} \tag{6}$$

Eq. (4) and Eq. (5) can be combined to obtain $\overline{Q^2}$

$$\overline{Q^2} = \frac{S\bar{\alpha}\pi\left\langle \overline{p_Q^{\ 2}} \right\rangle}{\rho_0^{\ 2}\omega^2} \tag{7}$$

Substituting the previous equation in Eq. (4), gives

$$\frac{\overline{W_{rad}}}{\overline{F^2}} = \frac{\overline{a_Q^{\ 2}}\rho_0}{\left\langle \overline{p_Q^{\ 2}} \right\rangle 4\pi c_0} \tag{8}$$

where the acceleration response of the structure is given by $a_Q = j\omega v_Q$, and can be obtained also by an average of different values corresponding to different source positions in the room. The previous equation can be used alongside the spatially-averaged squared transfer mobility $\left\langle |Y_t|^2 \right\rangle$ in order to obtain the radiation efficiency.

3. Measurement set-up

Two upright piano soundboards were available for the tests. These were completely stringed but with de-tuned strings, and fitted on the frame. The soundboards differ in the number of ribs, bays, and construction.

One soundboard was made of laminated spruce wood, with a core attached to two surface layers, and had 9 ribs and 10 bays, as can be seen from Figure 2 (left). This soundboard had a width of 1.40 m, a height of 0.88 m and a thickness of 8 mm. The other soundboard, Figure 2 (right), was made of solid Sitka spruce, and had 10 ribs and 11 bays. Dimensions were: width 1.38 m, height 0.895 m and thickness 8.5 mm. In this study the first soundboard is referred to as the laminated soundboard, and the second as the tone-wood soundboard.

Figure 2. Laminated soundboard (left) and Tone-wood soundboard (right).

3.1. *Acoustic power measurement setup*

To measure the acoustic power radiated by the soundboards they were placed individually in the reverberant chamber of the Institute of Sound & Vibration Research of the University of Southampton. The chamber has a volume of 348 m^3 and a surface area of 302 m^2. The room has non-parallel walls and diffusing panels to ensure a diffuse field. The equipment used consisted in miniature accelerometers placed at different positions on the soundboard bridges and a microphone placed on a rotating microphone boom to obtain the spatially averaged sound pressure in the chamber. Noise in the room was generated with loudspeakers, giving a reasonably flat averaged sound pressure level in the range 100-5000 Hz. The setup of the experiment is shown in Figure 3 and the sound pressure level developed in the chamber is presented in Figure 4 together with the background noise levels.

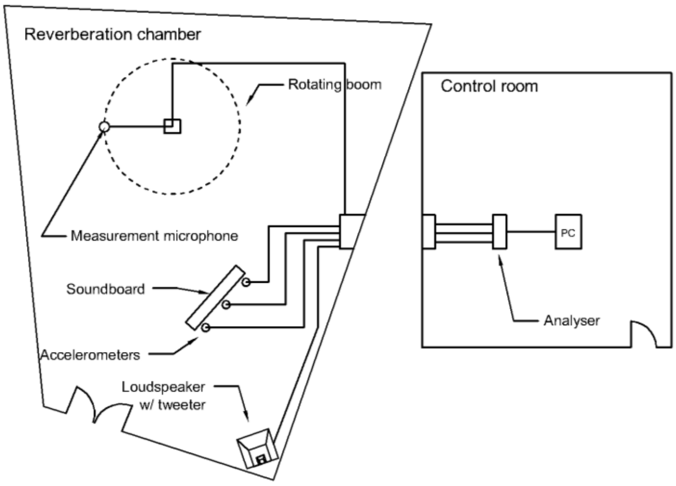


Figure 3. Experimental set up of measurements.

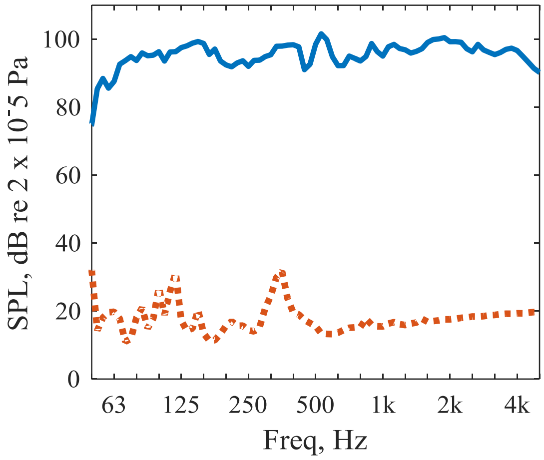


Figure 4. SPL present in the room during measurements (solid line) and background noise (dotted line).

Accelerometers were placed on the bridges, as this is representative for the real string excitation point. They are identified by the notes of the strings to which they are adjacent: they were at the locations of the notes C5 and A1 as shown in Figure 5.

Figure 5. Position of forcing/measurements points (left) and measurement grid for average mobility (right).

3.2. Vibration test set-up

The objective of this test was to obtain the spatially-averaged mobility and the driving point mobility at different points along the bridges of the two soundboards. The equipment used consisted of a Polytec PSV Scanning Vibrometer and an impact hammer.

The laser vibrometer was used to scan a grid of measurement points on the rear of the soundboards. The measurement grids consisted in roughly 200 points on each soundboard, including those on the ribs. The resultant grid on the laminated soundboard is shown in Figure 5-right. The grids were chosen so that they would cover the whole area of the soundboard keeping three transversal points in each bay (the area between two adjacent ribs) and one on the ribs. The excitation force was applied to the points defined above (C5 and A1). The impact was given directly to one of the pins of those locations, as this resulted in a better response up to higher frequencies than a direct excitation on the bridge surface.

4. Results

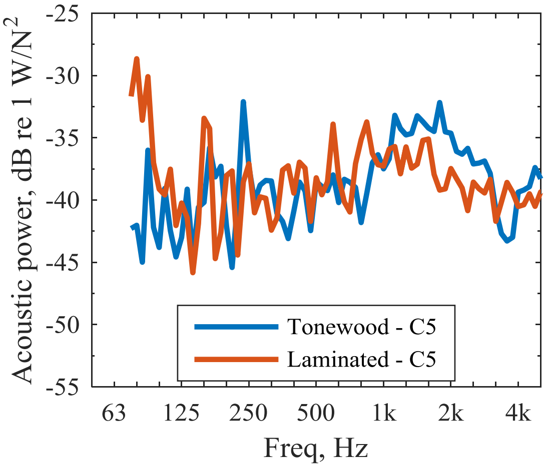
4.1. Sound power

Measured acoustic power and mobilities are presented in 1/12 octave bands in order to facilitate the comparison within and between figures. The results are presented for the soundboards without string tension.

Figure 6 shows the sound power for a unit force. This suggests that both soundboards, at both excitation points, follow a similar trend. At low frequencies (below 250 Hz) the acoustic power is characterised by strong peaks and dips and it is not possible to define clearly if one soundboard produces more acoustic power than the other.

Between 250 Hz and 1 kHz the level of fluctuations decreases and, for both soundboards, the acoustic power tends to increase. In this range, for a force at C5, the laminated soundboard has, on average, higher power levels than the tone-wood one. This difference can be up to 8 dB at some single frequencies (e.g. 850 Hz). If the force is given at location A1 the trend is the same but the tone-wood soundboard now produces higher acoustic power levels than the laminated one.

For both forcing points, the acoustic power has a broad peak in the region 1-2 kHz followed by a dip at 3-4 kHz. Between 1 and 3 kHz the acoustic power radiated by the tone-wood soundboard is 3-5 dB higher for the laminated one.



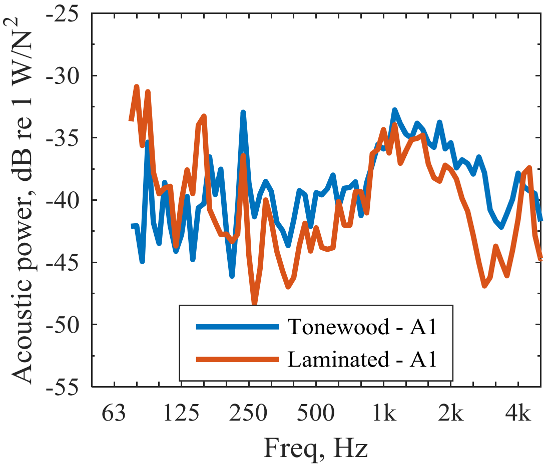


Figure 6. Acoustic power per unit force measured at location C5 (left) and A1 (right) for tonewood and laminated soundboards.

Besides the type of wood, the soundboards also differ in the number of ribs and manufacturing procedure. The type of wood can result in a different damping which can in turn be the reason for the differences in acoustic power, especially above 1 kHz. Additionally the mechanical power that can be transferred to the panel from the bridges is another possible mechanism that can explain differences in acoustic power. Furthermore, the different manufacturing procedure [13] can result in different curvature and residual stresses in the wood which can potentially affect the response.

The average vibration of the plate can be analyzed to understand the role played by damping, while effects due to differences in mechanical input power can be studied by measuring the driving point mobility. It is not easily possible to study the influence of the manufacturing procedure on the radiated sound and this is not considered in this paper.

4.2. Input power and average mobility

Figure 7 presents the real part of the driving point mobility at the same positions as above. This can also be interpreted as the mechanical input power due to a unit force transferred into the structure at the forcing point [14]. Figure 8 shows the measured average mobility for the two soundboards at the forcing points C5 and A1. In trying to understand the differences between the soundboards in term of acoustic power it can be considered that:

- the mechanical input power at high frequency is not affected much by damping but instead by the geometry and material of the bridge;
- the level of *average* mobility at high frequency depends strongly on damping and less on the local details at the forcing points [15].

The driving point mobility for position C5 (Figure 7-left) shows that up to 3 kHz there is a small tendency for the result for the tone-wood to be greater than that for the laminated soundboard. However this small difference in mechanical input power is not enough to explain the differences in acoustic power, especially above 1 kHz. Instead the average mobility is more helpful in this case: above 1 kHz for the tone-wood it is on average 2-3 dB above that for the laminated soundboard. From this forcing point one could conclude that the two soundboards differ in terms of damping and this causes the tone-wood one to radiate more sound than the laminated one.

However observing the driving point mobility and average mobility for the bass bridge at point A1 a slightly different conclusion can be drawn. Figure 7-right shows that driving point mobility of the tone-wood soundboard is greater than that for the laminated soundboard and also the difference between the two is comparable to the difference between the acoustic power radiated by them. Besides this, the two curves representing the average mobility are very similar (Figure 8-right) up to 2 kHz showing that below this frequency the overall response of the soundboard is not affected much by the type of wood. Above 2 kHz average mobility of the tone-wood is greater than that of the laminated soundboard. In this case it is more evident that the driving point mobility is mainly responsible for the differences measured in terms of acoustic power. A possible effect of the damping cannot be excluded from this result, particularly above 2 kHz, but differences in the local geometrical details of the bridge seem to be predominant.

To reinforce this, Figure 9 shows a close-up of the bass bridge for both soundboards. In particular there are differences in both the width of the foundation that the actual bridge is connected to, and in the thicknesses of the bridges. Further analysis will be needed to understand this more, possibly by modelling the two soundboards using finite elements including the details of the bridges. Alternatively to address finally the importance of the type of wood, two identical (geometrically and manufacturing) soundboards would be needed, differing only in the type of wood.

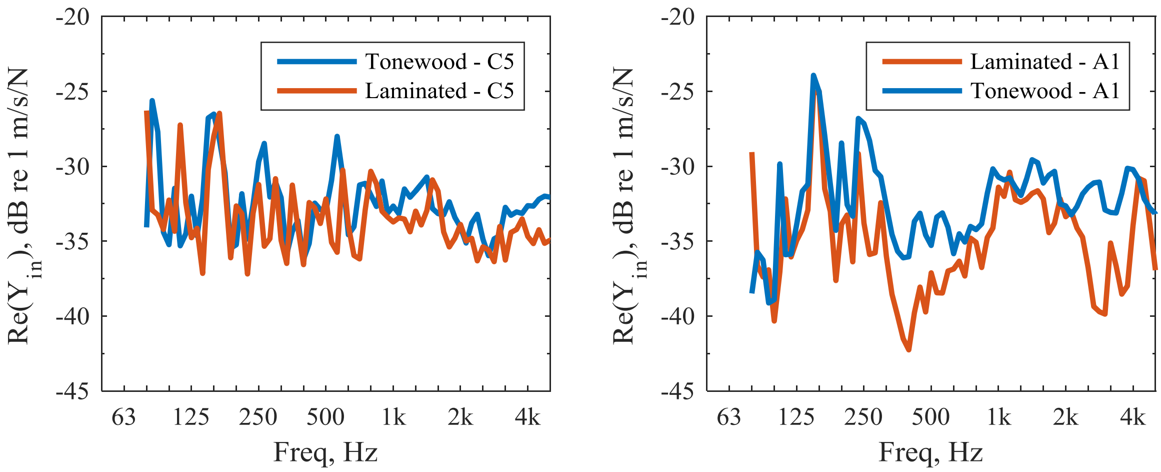


Figure 7. Driving point mobility measured at location C5 (left) and A1 (right) for tone-wood and laminated soundboards.

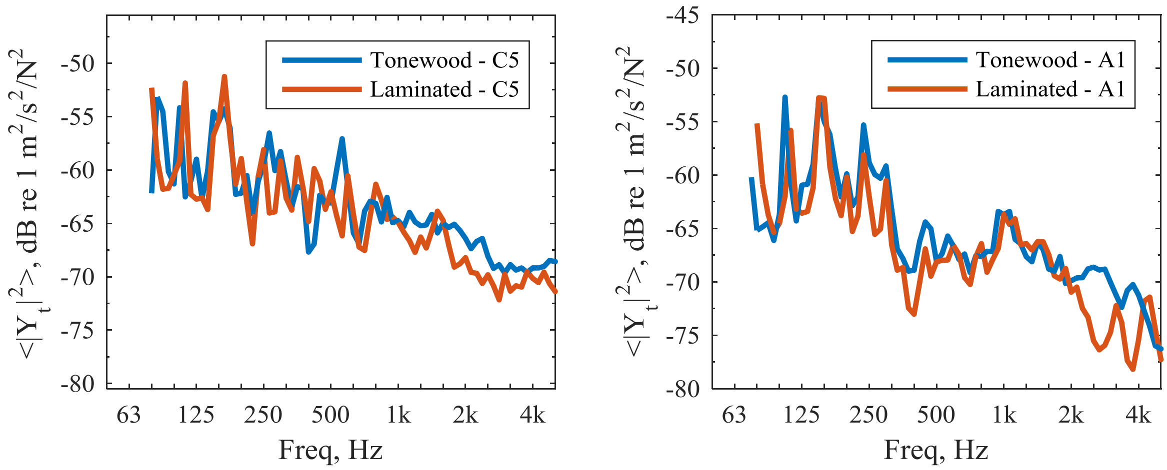


Figure 8. Average mobility measured for a force at location C5 (left) and A1 (right) for tone-wood and laminated soundboards.

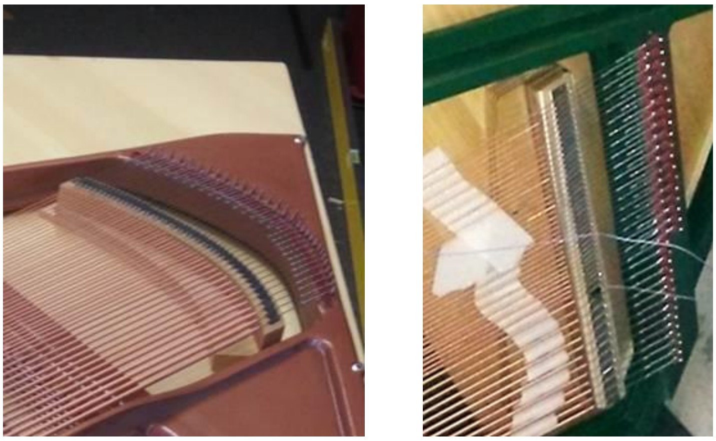


Figure 9. Close up of bass bridge of tone-wood and laminated soundboard

4.3. Damping estimation

To understand further the comparisons presented in the previous section, an estimation of damping loss factor can be made from the input power and averaged transfer mobility. To obtain this the input power can be equated to the dissipated power [14]. By assuming high modal overlap at high frequencies the latter can be found from the product of loss factor η, circular frequency ω and kinetic energy as:

$$W_{diss} = \eta\omega m\left\langle \overline{v^2} \right\rangle \tag{9}$$

with m being the soundboard mass and $\left\langle \overline{v^2} \right\rangle$ the spatially-averaged mean square velocity.

Rearranging this with the definition of mechanical input power results in:

$$\eta = \frac{\mathrm{Re}(Y_{in})}{\left\langle |Y|_t^2 \right\rangle m\omega} \tag{10}$$

As both driving point mobility Y_{in} and spatially-averaged transfer mobility $\left\langle |Y|_t^2 \right\rangle$ are available from measurements, the loss factor can be estimated from Eq. (10). Results for both forcing positions are presented in Figure 10. In both cases it shows that there is no clear tendency for one of the two soundboards to have a higher loss factor than the other. Indeed for force at position C5 the laminated soundboard has a higher loss factor between 1.5 kHz and 3 kHz, and this is aligned with the average mobility results of Figure 8-left but for position A1 the loss factor is very similar between 2 and 5 kHz while the tone-wood soundboard has a higher loss factor between 1 and 2 kHz. Clearly this result is not fully conclusive but it shows that both damping and driving point mobility can play a role in defining the differences in acoustic power. The first can be attributed to the type of wood while the second one is more closely related to the geometrical details of the bridges.

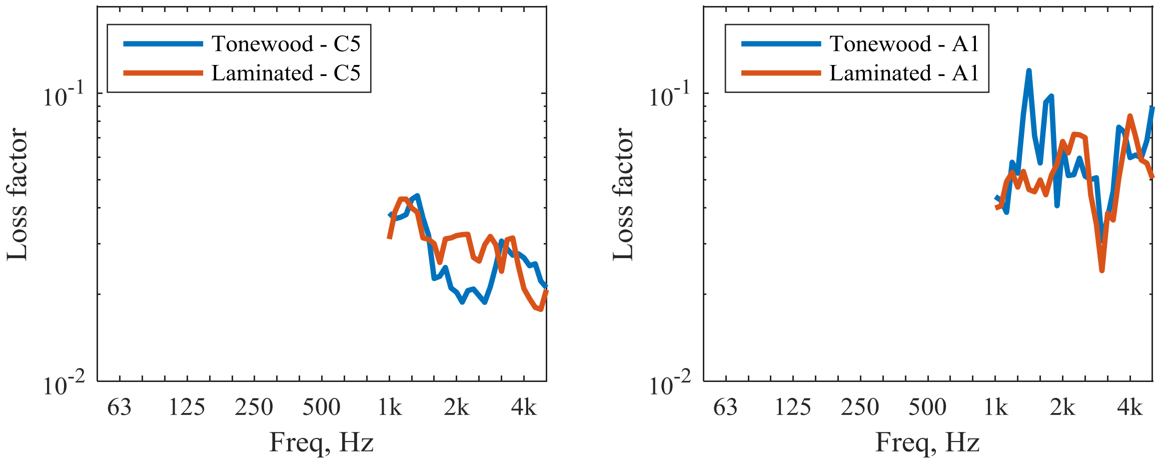


Figure 10. Loss factor as estimated for force at position C5 (left) and A1 (right).

4.4. Effect of tension

For the tone-wood soundboard, a study on the effect of string tension has been conducted. Figure 11 shows the acoustic power and average mobility for position A1. The lines labelled “No-Tension” correspond to a set-up with loosened strings, while the ones with “Tension” correspond to string tuned as normal. From both quantities it can be observed that below 500 Hz the results are characterised by the peaks of vibration modes. In this range the effect of tension in the strings is to move the peaks to higher frequencies and to decrease their magnitude. In other words there is an increase of both stiffness and damping (see also [16] and [7]). Above 500 Hz the effect of tension is negligible and both acoustic power and average mobility are very similar. Analogous results have been found for position C5.

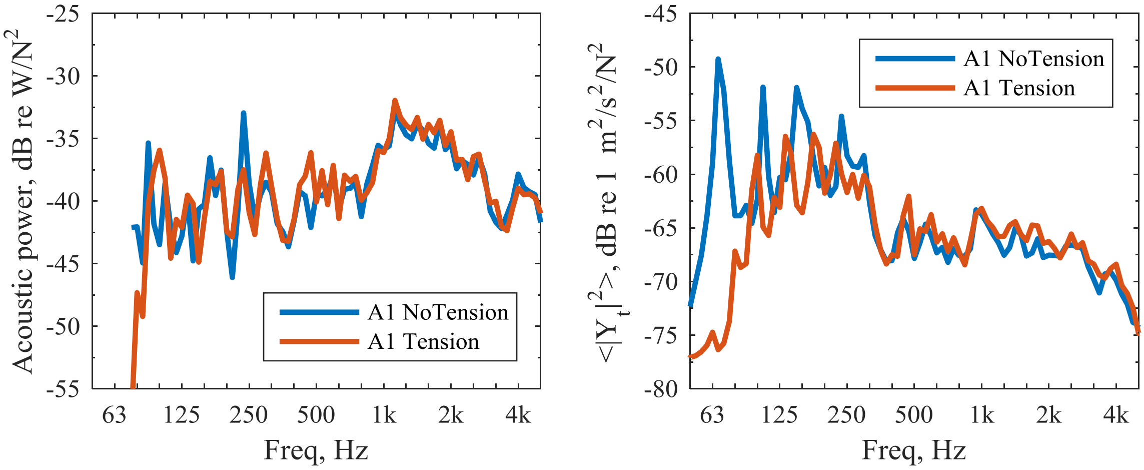


Figure 11. Effect of string tension on acoustic power (left) and average mobility (right). The lines labelled "NoTension" correspond to a set-up with loosened strings, while the ones with "Tension" correspond to string tuned as normal.

5. Conclusions

A method based on vibro-acoustic reciprocity in a reverberant environment was tested to measure sound power due to a unit force at the bridge of two different piano soundboards. One sample was made of solid spruce (tone-wood) while the other one by laminated spruce. Additionally, the driving point mobility and average mobility over more than 200 points on the soundboard surfaces were measured. The acoustic power of the tone-wood soundboard is consistently 3-5 dB higher than laminated one above 1 kHz, while at lower frequencies there is not a clear tendency for one to be higher than the other one. Possible reasons to explain this difference were sought in differences in loss factor and also in driving point mobility. Because the soundboards differ also in some geometrical and manufacturing details it was not possible to define differences solely in terms of the type of wood. In fact, comparison of driving point mobilities showed that the geometrical details of the bridges can also be of great importance.

Finally, the effect of string tension has been evaluated for the tone-wood soundboard by comparing acoustic power and average mobility before and after tuning the strings to their correct pitch. For both measured quantities the effect of string tension is important only below 500 Hz where it adds stiffness and damping to the structure. Above 500 Hz string tension was found to have negligible effect on structural and acoustic response.

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