Driving Point Mobilities of a Concert Grand Piano Soundboard in Different Stages of Production

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Abstract

In an on-going project, a series of driving point mobility measurements is taken on a concert grand piano soundboard. The piano is accompanied by measurements during the entire production process, performed at seven discrete stages of the instrument's construction. Mobility functions are obtained at 15 different driving point positions, corresponding to string termination points on the bass and treble bridges. Application of ribs and the bridge decrease the overall mobility by 10 dB each. Clamping the soundboard generates distinct resonance behavior in the low frequency range and greatly increases resonance frequencies. Stringing increases resonance frequencies and lowers their amplitudes. After gluing the soundboard into the rim, the mean mobility stays constant between 1 kHz and 5 kHz, a sudden rise in mobility cannot be confirmed.

1. Introduction

The impedance mismatch between strings and soundboard is a crucial factor for the actual sound produced by a piano. If the mismatch is too small the tone is harsh and short, if it is too great the tone becomes long but too soft [4]. Historically, piano manufacturers tried to find the optimum relation by experimenting with the structural design of the soundboard and strings.

The driving point mobility $Y(\omega) = v(\omega)/F(\omega)$ with ω being the angular frequency is a widely accepted parameter to describe the frequency dependent behavior of musical instrument parts as a ratio between a complex velocity response v and a complex excitation force F for one specific point on the vibrating structure (see [6] for a detailed description of mobility concepts). For the present work, only the direction normal to the soundboard is considered.

Wogram is the first to describe the vibrational behavior of a piano soundboard by means of driving point impedances [14]. He performs measurements on an upright piano soundboard, with and without strings. Subsequent publications question the correctness of his data in the higher frequency range: the impedance falloff above 1 kHz, inversely proportional to frequency, is considered to appear due to decoupling of excitation device and soundboard [9, 7]. Nakamura presents mobility measurements for a completely assembled upright piano [12]. Consistent with Wogram, he observes an increase of mobility above 1 kHz. Even though the resonances of his measurement devices are located in the regarding frequency range, he explains the increase with the ribs becoming fixed edges for high frequency vibrations. Giordano performs impedance measurements on a fully assembled upright piano [9]. He confirms a decrease of impedance above 2.5 kHz for measurements at the bridge. Ege et al. give a synthetic description for the mobility of a fully assembled upright piano based on three parameters: modal density, mean loss factor and structure mass [7]. They explain a rise of mobility in high frequencies to be dependent on the inter-rib effect, to occur when the wavelength equals twice the rib spacing. A transition frequency range between 2 kHz and 3 kHz, from which onward the soundboard motion is governed by the ribs, is also proposed by Berthaut [3] and experimentally confirmed by Moore [11]. After Conklin [5], the attenuation effect due to ribbing should occur at 1.2 kHz for conventional rib spacing. Conklin [4] presents mobility measurements of a concert grand piano (with conventional rib spacing) with and without strings. Stringing seems to increase resonance frequencies and to lower peak values. No influence of downbearing on mobilities is observable above 1 kHz. Contradictory to previous publications, his data does not confirm a mobility increase at high frequencies (he presents mobility functions up to 3.2 kHz).

The present work tries to elaborate on some of the issues and questions remaining with regard to these, often contradictory, findings. It is aimed at understanding the evolution of, and changes in, the vibratory behavior of the soundboard during different stages of the production process, instead of taking only the finished instrument into account, as has been done in previous research.

2. Method

Measurements are taken on a concert grand piano in seven different stages of production, starting with the glue-laminated strips of spruce wood, and ending with the completely assembled piano in concert tuned state (denoted as PROD 1-7, see Table 1). The soundboard is excited at 15 positions associated with string termination points on the bass and treble bridges (denoted as POS 1-15, see Table 2). An impact hammer (*Kistler 9722A500*) with 0.1 kg head weight is used for excitation. For the sake of comparison, a miniature impact hammer (*Dytran 5800 SL*) with a mass of 0.01 kg is used for a series of measurements. Although above 4 kHz the induced energy is greater than for the heavier hammer, the mobility functions obtained do not differ below 5 kHz. The heavier hammer is chosen for the experiment due to the much greater amount of energy transmittable in the frequency band up to 2 kHz. The response is captured with a piezoelectric transducer (*PCB 352C23*) with a mass of 0.2 g, situated on the bridge with a distance of approx. 2-3 mm from the hammer impact position. Since the transducer is sensitive to acceleration, the data is numerically integrated to obtain velocity values. For PROD 1-4 the soundboard lays on felt in the exact same profile as it is later glued into the rim. The boundary conditions for PROD 1-4 can therefore be considered as simply supported. For PROD 5-7 the boundary conditions can be considered to be clamped. Deflection shapes at low frequency resonances are obtained from microphone array measurements of the soundboard in all prior mentioned production stages. A total number of 1289 microphones cover the entire surface with an inter-mic distance of 40 mm. The soundboard is excited by an electrodynamic shaker with an exponential sine sweep, impulse responses are derived with the SineSweep technique proposed by Farina [8]. The measured sound pressure can be back propagated to the soundboard surface with a minimal energy method proposed by Bader [2, 1].

Table 1: Denotation of different production stages.

PROD	
1	blank soundboard (glue-laminated strips of *sitka spruce*)
2	after the ribs have been attached
3	after the bridge has been attached
4	after the ribs have been notched
5	after the soundboard has been glued to the rim
6	after application of the iron frame and stringing
7	after regulation, voicing and tuning - concert tuned state

Table 2: Corresponding keys to driving point positions (1-4: bass bridge, 5-15: treble bridge).

POS	1	2	3	4
Key	A0	F1/G1	B1	E2

POS	5	6	7	8	9	10	11	12	13	14	15
Key	F2	G2	A2/B2	D3	F3/G3	B3	F4	C5/D5	B5	A6/B6	C8

3. Results

3.1 General development through the production process

In Figure 1 (left) mobility functions dependent on production stage are plotted vs. frequency, where dark colors imply low, and bright colors imply high mobility values. Consequently, clear bright lines illustrate resonances. That way the general development of driving point mobilities through the production process can be illustrated: For the first production stage (PROD 1), the blank soundboard has an overall high level of mobility. The first two resonances at 13 Hz and 25 Hz (see Figure 3) are the only remarkable ones. Attachment of the ribs (PROD 2) decreases the overall level of mobility. A more distinct resonance behavior is observable up to 300 Hz. Attachment of the bridge (PROD 3) further decreases the overall mobility level. Notching the ribs (PROD 4) has no impact on the general mobility. Changing the boundary conditions by gluing the soundboard into the rim (PROD 5) affects the vibrational behavior fundamentally in the low to mid frequency range: up to 300 Hz distinct resonances appear. Stringing (PROD 6) increases the frequencies of those resonances and lowers their amplitudes. Besides a slight resonance frequency increase, the voicing and tuning process (PROD 7) has no remarkable influence on the vibrational behavior of the soundboard. Figure 1 (right) focuses on mobilities for PROD 5 dependent on the driving point position. An upper frequency limit for distinct resonances between 250 Hz and 300 Hz is observable. Driving point positions near the ends of the bass bridge (POS 1 and 4) and treble bridge (POS 5 and 15) have generally higher mobility levels than the rest. The clamping particularly prevents low frequency resonances in the treble register. In the highest octave, the soundboard only shows some spare resonances between 200 Hz and 300 Hz. Figure 2 shows operating deflection shapes exemplary for the first three soundboard resonances. Figure 3 shows development of their frequencies through the production process.

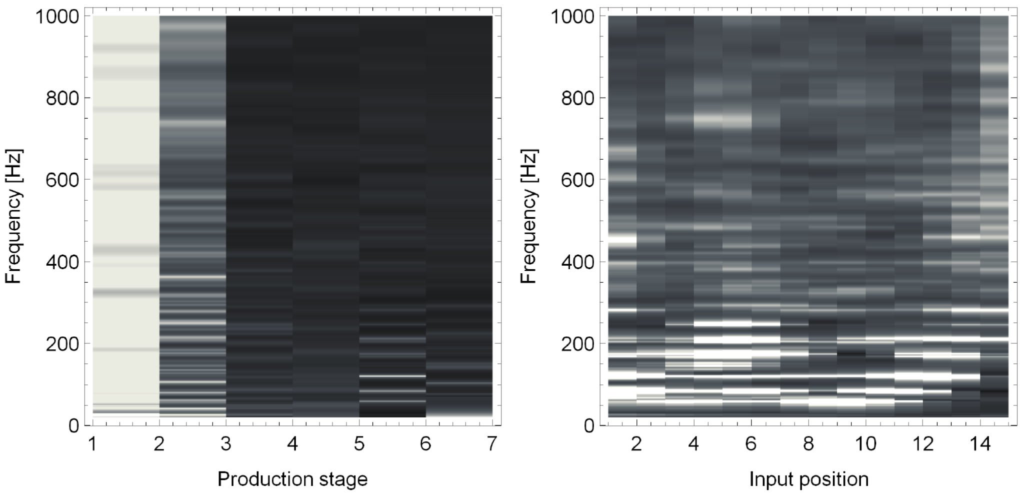

Figure 1: Mobility maps for (left) average mobility per production stage and (right) mobility per driving point position for PROD 5. Dark colors imply low, and bright colors imply high mobility values.

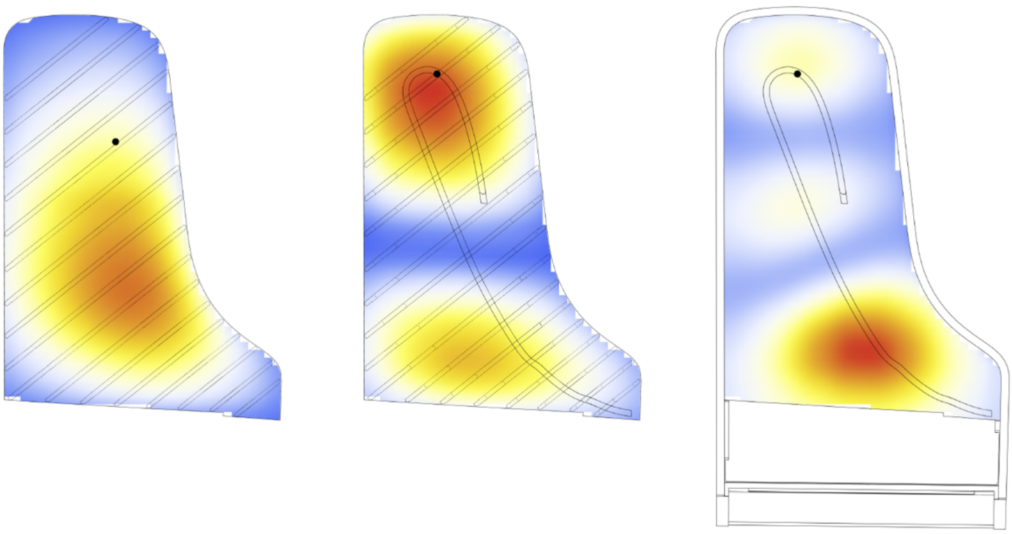

Figure 2: Modulus of operating deflection shapes for the first three soundboard resonances. Black dots depict driving point positions. (a) PROD 2, POS 3, 15 Hz, (b) PROD 4, POS 1, 27 Hz, (c) PROD 5, POS 1, 113 Hz.

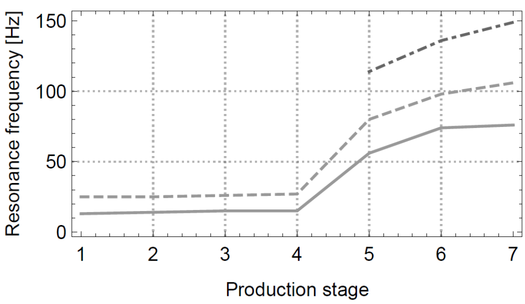

Figure 3: Frequencies of the first three soundboard resonances per production stage. Corresponding to operating deflection shapes in Figure 2: (a) line, (b) dashed, (c) dot-dashed. Deflection shape (c) is not observable in production stages PROD 1-4.

3.2 Detailed view on exemplary mobility functions

Figure 4 shows modulus of mobility vs. frequency at exemplary driving point positions for the four most influential construction steps. Each function is the mean of five independent measurements. Without ribs, the soundboard exhibits no resonance characteristic except for the first two resonances at 13 Hz and 25 Hz. Above 50 Hz, the mean mobility remains constant. Attaching the ribs decreases the mobility level by 10 dB in the low and mid frequency range. In the range up to 500 Hz resonance characteristics arise (see Figure 4 (a)). Application of the bridge further decreases overall mobility by 10 dB and 10-20 dB above 1 kHz (see Figure 4 (b)). Besides a small increase of resonance frequencies in the low frequency range, notching the ribs causes no observable alteration of mobility functions. A major change in low frequency behavior evolves when the soundboard is glued into the rim, observable as a development of strong resonance peaks up to 300 Hz. From 500 Hz to 5000 Hz the mean mobility stays constant (see Figure 4 (c)). Up to 350 Hz, the application of strings and frame causes an increase of resonance frequencies of approx. 20 Hz (see Figure 3) and a decrease of resonance amplitudes by approx. 10 dB (see Figure 4 (d)).

4. Discussion

The decrease of general mobility by application of ribs and bridge is assumed to result of stiffening the soundboard. Clamping the soundboard into the rim, and thereby changing the boundary conditions, has the most prominent effect on its vibrational behavior: Below 300 Hz sharp resonances appear. An upper frequency limit for distinct resonances between 250 Hz and 300 Hz is observable and confirms data presented by Suzuki [13] and Berthaut [3]. Up to 350 Hz, the application of strings and frame causes an increase of resonance frequencies of approx. 20 Hz and a decrease of resonance amplitudes by approx. 10 dB. This is in good agreement with Conklin [4] and Mamou-Mani [10]. In contrast to Conklin, who observed an influence of stringing for a range up to 1 kHz, in the present case the effect is only observable up to 350 Hz. In the frequency range above 1 kHz the presented results cannot confirm a sudden increase in mobility. The mean mobility stays more or less constant for the cases when the soundboard is clamped.

The empirical findings will contribute to the formulation of a real-time physical model to help piano makers estimate the impact of design changes on the generated sound.

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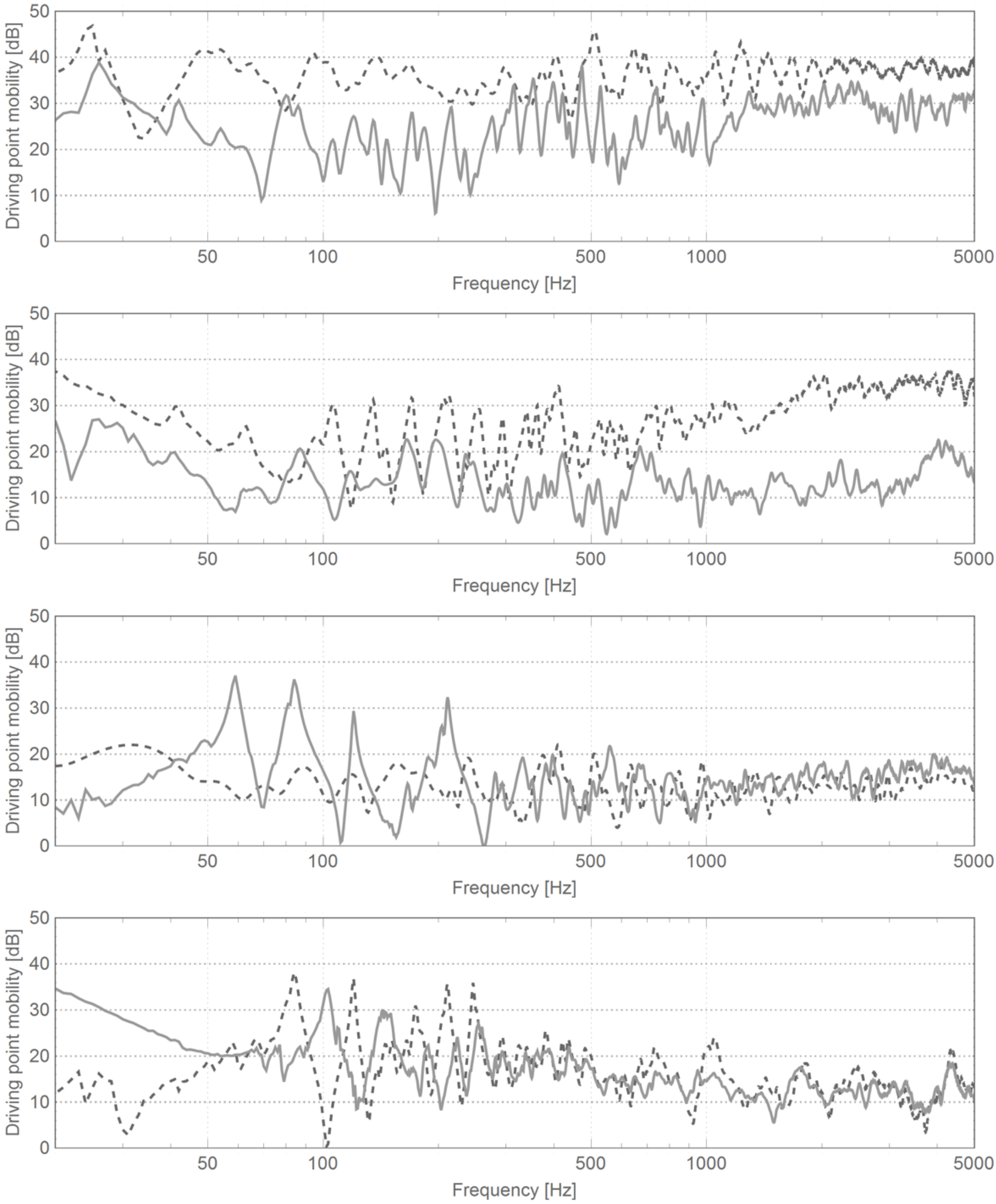

Figure 4: Modulus of mobility for different stages of production before (dashed) and after (solid) the modification is applied. From top to bottom: (a) Attachment of ribs, POS 5 (b) Attachment of the bridge, POS 11 (c) Gluing the soundboard into the rim, POS 10 (d) Stringing, POS 5.

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