Evaluation of a Digital Grand Piano for Vibrotactile Feedback Experiments and Impact of Finger Touch on Piano Key Vibrations

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Abstract— **There are suggestions that vibrotactile feedback in piano playing is important for the quality perception of the instrument, as well as for the precise timing and dynamic control. To objectively measure and understand the influence of vibrotactile feedback in the pianist-piano interaction, we plan experiments with a digital hybrid grand piano - the Yamaha AvantGrand N3X - that simulates piano key vibrations with a rendering system. In this paper, we evaluate piano key vibrations of this instrument with a laser Doppler vibrometer and compare the vibrations to measurements with an acoustic grand piano. The peak levels of the vibrations (13 to 35 μm for the acoustic grand piano and 16 to 25 μm for the AvantGrand) are comparable but the rendering system has limitations outside the frequency range from 150 to 400 Hz. Furthermore, the perceptibility of the vibrations generated by key presses with the left hand at the right hand playing position and vice versa are investigated. Finally, the impact of the finger on the vibrations during different stages of a key press is analyzed and it is demonstrated that the finger influences the displacement levels and the spectral weighting of the piano key vibrations.**

I. INTRODUCTION

Playing a musical instrument is a multi-modal task, where the musician interacts with his instrument based on sensory feedback. It is generally agreed that the most important feedback path for playing a musical instrument is the auditory one but also haptic feedback plays a central role, e.g. for learning the behavior of a musical instrument and for constantly observing its state, as pointed out by O'Modhrain [1].

Haptic feedback is the combination of force feedback (the mechanic reaction of the instrument) and vibrotactile feedback (vibrations that are felt at the contact points with the instrument). In piano playing, the principal source of force feedback is the response of the piano action to the finger touch. Gillespie et al. [2] presented a device that was capable of simulating and rendering the force feedback of a grand piano action in real-time.

As demonstrated by Askenfelt and Jansson [3], the piano provides vibrotactile feedback at the contact points between the pianist and the piano. The fingers are in contact with the keys and the feet are in contact with the pedals. Pianists are often not aware of or not concerned about these vibrations as noted by Keane and Dodd [4]. They also reported that some pianists attach modifications of piano key vibrations to a different cause, such as changes in tone or loudness[1].

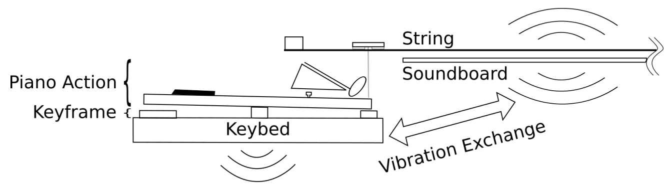

Fig. 1: Simplified schematic of the vibration paths in a grand piano adapted from Askenfelt [10]. The vibrations on the keybed are generated by the collision of the key with the keyframe when a key is pressed (broadband component), the soundboard is excited by the vibrations of the string that is struck by the hammer (tonal component). The soundboard and the keybed are acoustically coupled through the structure of the piano.

Fontana et al. [6] showed with a detection experiment that the piano key vibrations are perceivable up to key A4 (440 Hz), when conscious attention is payed to the vibrations. It was shown by Keane and Dodd [4] and Fontana et al. [7] that vibrotactile feedback can have an influence on the perceived quality of the instrument and it was suggested that it has an influence on dynamic control and timing in piano playing [7].

Measurements of vibration detection thresholds at the fingertip for sinusoidal signals with a duration of 1 second have been reported by Verrillo [5]. Vibrations up to 1 kHz can be sensed, the threshold is frequency dependent, and the fingertip is most sensitive in the frequency region from 200 to 300 Hz, where it can detect vibrations with displacements as small as 0.1 μm.

Keane [9] showed that not just the sound of the piano but also the vibrations on the keys consist of a tonal and a broadband component. The broadband components are generated mechanically by the collision of the key with the keyframe when a key is pressed and the stop of the key after it was released. The tonal component originates from the vibrations of the strings. The vibrations are exchanged between keybed and soundboard through the structure of the piano as observed by Askenfelt [10] and outlined in Fig. 1.

In a recent study [11] we presented piano key vibration measurements of different grand pianos and upright pianos and demonstrated that the vibrations are above the detection

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[1]The subjective impression of the professional pianist in our study during a blind A / B comparison with the vibrotactile feedback rendering system of the AvantGrand turned on and off was attached to a change in force feedback.

thresholds of Verrillo [5]. We measured peak displacement levels up to 80 μm and observed that the frequency spectrum of the vibrations is dominated by frequencies lower than 500 Hz.

In this paper, we evaluate the capability of this instrument for the use in vibrotactile feedback studies and present a first result of a pilot experiment, where we investigated the influence of the finger on the piano key vibrations.

The content is structured as follows: section II explains the measurement setup, presents a brief overview of the haptic feedback of the AvantGrand and discusses the controls of the vibrotactile feedback rendering system of this instrument. Thereafter in section III, piano key vibration measurements from the AvantGrand are compared to those of an acoustic grand piano. After that, the perceptibility of the vibrations at the left and right hand position are evaluated, before we study the influence of the finger on the piano key vibrations. In the last section, the results are concluded and an outlook is presented.

II. METHODS

In this section we present the measurement method and the configurations. Several aspects of the AvantGrand piano are discussed with focus on the parts that contribute to the haptic feedback of the instrument.

A. Measurement Setup

The measurements were made with a professional pianist performing on a AvantGrand N3X piano. The setup is the same as in [11] and consisted of a laser Doppler vibrometer (LDV), with a velocity range of $\pm$ 50 mm/s and a resolution of 0.6 μm/s. The vibration velocity was measured perpendicular to the playing surface of the keys. A calibrated microphone recorded the radiated sound. In addition, the audio signal of the balanced output and the MIDI performance data of the AvantGrand were recorded. All analog signals were captured with a sound card sampling at 48 kHz with a resolution of 16 bit.

B. Post-processing

To remove low frequency vibrations due to motions of the stand and ground vibrations, we processed the vibrometer signal with a high pass filter at 20 Hz. To account for the frequency dependency of the vibration detection threshold at the fingertip by Verrillo [5], a frequency weighting filter was used to equalize the frequency response and shift the threshold to 0 dB. This filter was introduced in [11]. The displacement was calculated from the vibration velocity recording. Displacement signals in dB are calculated relative to 1 μm hereafter.

C. Haptic Feedback and the Vibrotactile Feedback Rendering System of the Yamaha AvantGrand N3X

The AvantGrand N3X is the latest model of the family of digital hybrid pianos from Yamaha. The concept of the AvantGrand series of instruments is to have all the advantages of a living-room sized digital instrument but to replicate the sound and haptic sensation of a concert grand piano. For more details see [12] or the website of the company[2]. The piano action of the AvantGrand N3X features gradually weighted keys and hammers. The piano key vibrations are simulated to complete the illusion of an acoustic grand piano.

A simplified schematic of the AvantGrand piano is presented in Fig. 2. The piano action has the same operation mode as a typical grand piano action but differs in the following way: some of the parts are made of synthetic material, there is an optical sensor system to pick up hammer and key movement, a weighted dummy hammer hits a padded rail instead of a felted hammer hitting a string, there is no string-damper, and the key lengths are rather short (around 47 cm for piano key C4). A sensor system with the same working principle was explained by Goebl in [13].

The generated sound is played back through a loudspeaker system and three transducers that directly excite solid parts of the instrument. The construction and the wood of the keybed and keyframe are similar as those encountered in acoustic pianos.

To transmit the "virtual" string vibrations through the keys to the fingertips of the player, Yamaha implemented a vibrotactile feedback rendering system: the so-called Tactile Response System (TRS). The piano keys are excited through a transducer that directly excites the keybed, see Fig. 2. To the authors' knowledge, the AvantGrand instruments are the only digital pianos on the market that implement such a system.

1) Broadband and Tonal Component of the Piano Key Vibrations: Fig. 3 shows a typical time signal and spectrogram of the piano key vibrations measured on the AvantGrand. The signal can be divided into three parts: a broadband component (a) that is generated during key press when the key is stopped by the keyframe, a tonal component (b) during the time when the key is held pressed down (key sustain), and a second broadband component (c) when the key is

[2]https://europe.yamaha.com/en/products/musical_instruments/pianos/avantgrand/n3x/index.html, last accessed 10/16/2017

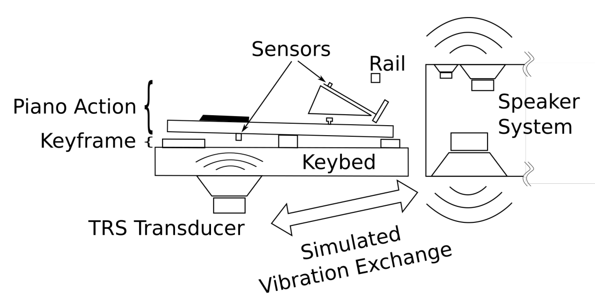


Fig. 2: Simplified schematic of the AvantGrand N3X piano. In contrast to the acoustic grand piano, the vibration exchange between keybed and soundboard is simulated. The broadband component of the piano key vibrations is generated mechanically with the piano action. The transducer of the Tactile Response System (TRS) generates the tonal component by exciting the keybed.

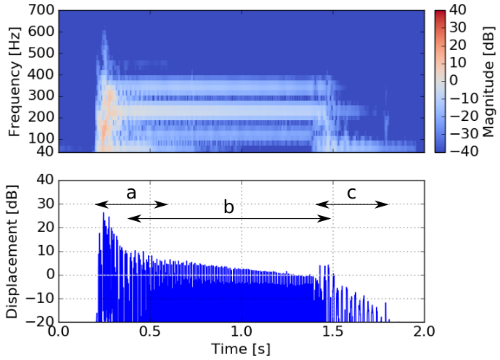


Fig. 3: Typical time signal and spectrum of the vibration displacement measured on the AvantGrand. The LDV was measuring piano key D3 that was silently held down with the index finger. Piano key A2 (110 Hz) was played. The signal consists of the following parts: (a) broadband component generated by key attack, (b) tonal component during key sustain, (c) broadband component generated by key release.

released and stopped at the rest position. The broadband components mainly depend on the mechanical properties of the piano action, the keybed, and the keyframe but especially the level also depends on finger touch. The tonal component is generated by the TRS and depends on the played note and on the intensity of the keystroke (dynamic level).

2) Controls of the Tactile Response System: The intensity of the vibrations generated by the TRS can be controlled in a step-wise manner. The measured envelope of the vibration displacement for different settings are shown in Fig. 4. The same piano key was played with touch and dynamics as similar as possible. The system is turned off with TRS = 0 and with TRS = 1, 2, 3 the intensity of the vibrations is gradually increased. The level difference for TRS = 0 and TRS = 3 measures 18 dB. The step size amounts to roughly 6 dB per intensity increase.

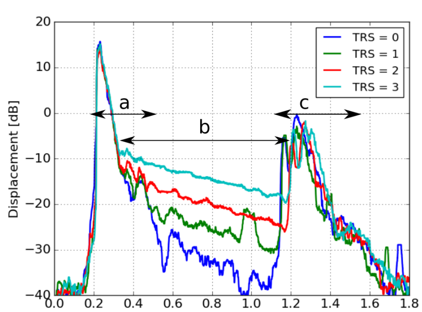


Fig. 4: Time signal envelopes of the measured vibrations for different settings of the Tactile Response System (TRS) of the AvantGrand. The measurements were made on the silently held down piano key A2 and piano key C3 (131 Hz) was played. Parts (a), (b), and (c) refer to the stages of key attack, key sustain, and key release, see Fig. 3.

Also the influence of the piano sound setting[3] and the master volume control was evaluated. The weighting of the harmonics and the intensity depend on the sound setting. Finally, also the subwoofers of the loudspeaker system actuate the instrument body and therefore also influence the vibrations on the keys, see noise floor in Fig. 4 for TRS = 0.

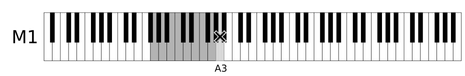
For this evaluation we use the default sound (called CFX Grand), a TRS level of 2, and master volume control at 3-o'clock (around 4/5).

D. Measurement Configurations

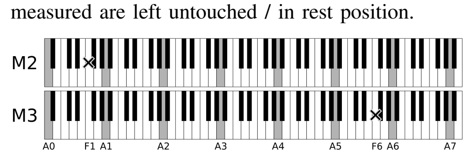
The four configurations considered in this paper are summarized in Table I.

TABLE I: Configurations: played notes are highlighted in gray, keys that are silently held down or touched are marked with a gray texture (see key A3 in M1 and D3 in M4), the measurement points of the LDV are marked with crosses. Configurations M1, M2, and M3 correspond to configurations presented in [11].

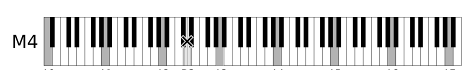
M1: To compare the vibrations of the AvantGrand to measurements with acoustic grand pianos a sequence of 20 quarter notes was played with the left hand, while A3 was pressed down silently by the index finger of the right hand.



M2 & M3: The vibrations at two piano keys (F1 and F6) were measured to evaluate the piano key vibrations close to typical left and right hand positions. Notes A0 to A7 were depressed 4 times at two different dynamic levels (mezzo-forte (mf) and forte (f)). The keys where the vibrations are measured are left untouched / in rest position.



M4: The influence of the finger on the vibrations of piano key D3 is studied in four conditions (I0, I1, I2, I3) that correspond to different stages of a key press. Notes A0 to A7 were played with two dynamic levels (mf and f) and two kinds of touch (pressed and strucked touch).



III. RESULTS

Hereafter, the piano key vibrations measured on the AvantGrand piano are evaluated by a comparison. Subsequently, the vibrations close to typical left and right hand positions on the keyboard are evaluated and finally the influence on the vibrations of the finger in contact with the key is analyzed.

[3]The different sounds are referred to as voices in the user manual. There are five acoustic piano sounds to select from.

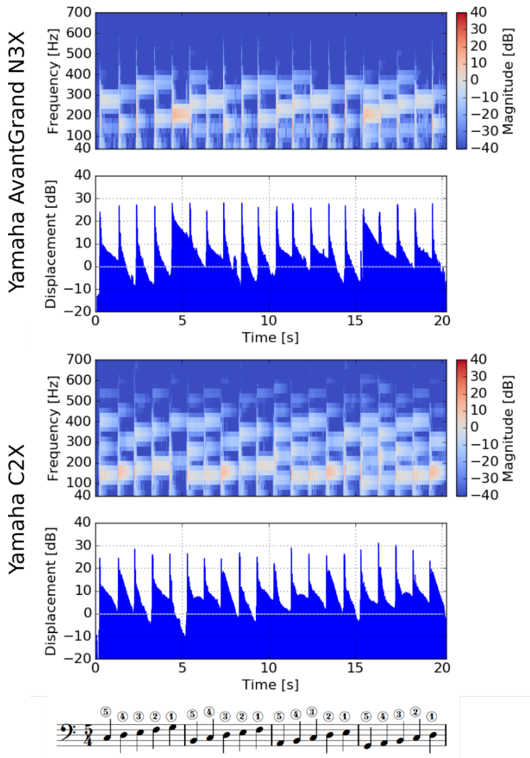


Fig. 5: Comparison of the piano key vibrations measured on the Yamaha AvantGrand and the Yamaha C2X acoustic grand piano. The vibration displacement signal is frequency weighted to equalize the frequency dependency of the detection threshold from Verrillo [5] and to shift it to 0 dB. The signals are aligned to the score.

A. Comparison to the Piano Key Vibrations of an Acoustic Grand Piano

In this subsection, we compare the measurements of the AvantGrand N3X piano to the measurements with the Yamaha C2X acoustic grand piano presented in [11]. We show that the level and spectrum of the broadband components of the vibrations are alike but that there are differences in the tonal part due to limitations of the vibrotactile feedback rendering system of the AvantGrand.

The time signals and spectrograms of the measurements from configuration M1 are depicted in Fig. 5. The response of the Yamaha C2X acoustic grand piano is representative for grand pianos and we chose it for this comparison because the piano actions of the C2X and the AvantGrand have commonalities, especially in size.

The time signals have the same range and the vibrations of both instruments are above the detection threshold of Verrillo [5] and thus perceivable[4] for the notes played in this configuration. The broadband components resemble to a high degree. The peak levels measure 22 to 31 dB (13 to 35 μm) for the acoustic grand piano and 24 to 28 dB (16 to 25 μm) of the AvantGrand piano. The spectrograms differ in the following way: the tonal components of the vibrations generated by the AvantGrand are band-limited to 400 Hz and the magnitudes below 150 Hz are 10 dB and more lower than those measured on the acoustic grand piano. Also the notes or the frequencies respectively, where the resonance occur are not the same (see note G3 (196 Hz) for the AvantGrand piano and note D2 (147 Hz) for the acoustic grand piano).

Concluding this comparison, the vibration displacement levels and the broadband components are comparable to the ones measured on acoustic pianos. The main differences are in the tonal components of the vibrations, caused by electro-acoustical properties of the vibrotactile feedback rendering system.

[4]This fingertip vibration threshold was obtained for sinusoidal signals with a duration of one second and a contact area size of 28 mm^2. As explained in [11] the contact area of the finger pad is 2-3 times higher, that is to say the threshold in piano playing is expected to be at least 3 dB lower due to spatial summation.

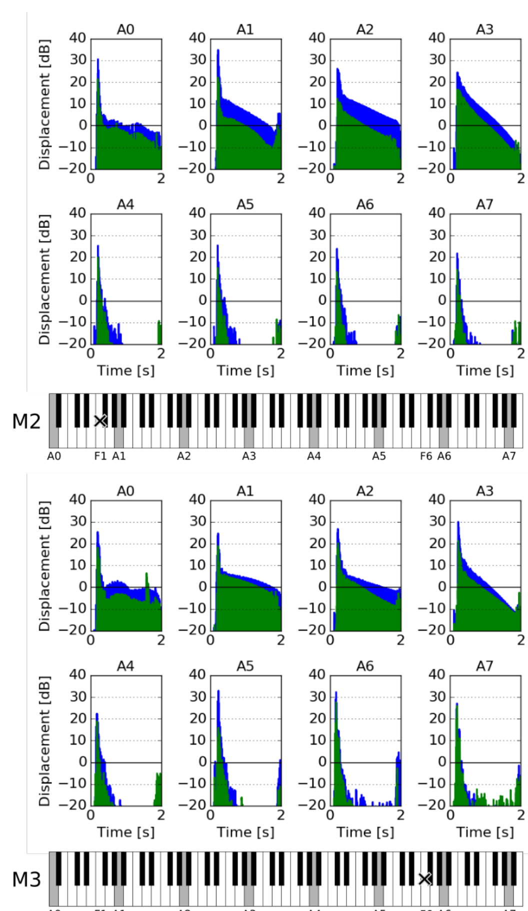


Fig. 6: Single key strokes of all A notes were recorded with two dynamic levels (mf and f) in configuration M2 and M3 on the AvantGrand. The time signals are averages over 4 keystrokes. Displacement signals are processed with the frequency weighting filter and calculated relative to 1 μm. The keys measured with the vibrometer are left untouched / in rest position for these configurations.

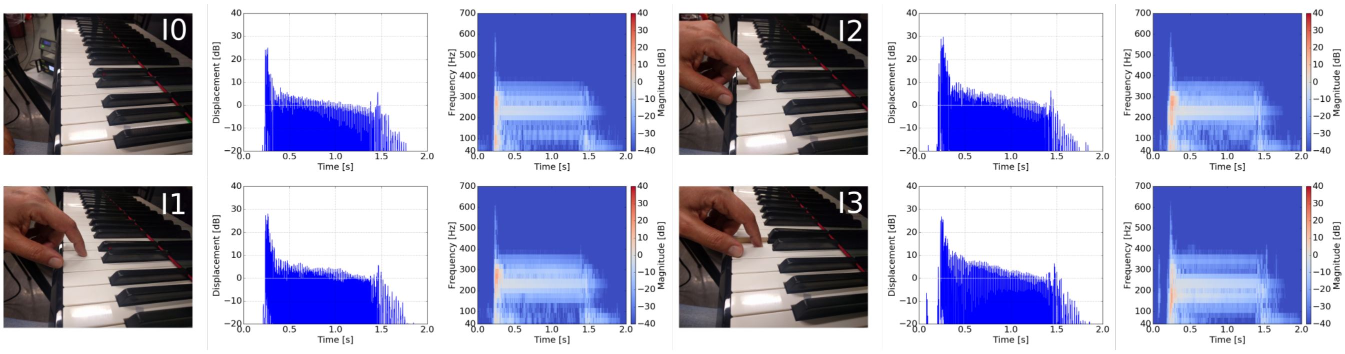


Fig. 7: Influence of the finger on the key vibrations under different conditions corresponding to different stages of a key press: I0, I1, I2, and I3. Piano key A1 (55 Hz) was played and piano key D3 was measured under four finger touch conditions. The measured MIDI velocities of the notes were in the range from 101 to 109 (this corresponds to forte level). The conditions are the following: I0: key in rest position / untouched, I1: the index finger touching the playing surface (such as at the beginning of a keypress), I2: key half pressed with the index finger (such as in the middle of a keypress), I3: key held fully down by the index finger (such as in the sustain stage of a note). Displacement signals are processed with the frequency weighting filter and calculated relative to 1 μm.

B. Perceptibility of the Vibrations at the Left and Right Hand Position

In this part, the piano key vibrations of the AvantGrand are evaluated at two different positions on the keyboard. These positions correspond to rather extreme but close to common left and right hand positions. The goal of this comparison is to assess, if vibrations generated by keystrokes with the left hand fingers can be felt by the fingers of the right hand and vice versa. Also the influence of the dynamic playing level is examined.

The piano key vibration displacements measured in configurations M2 and M3 are shown in Fig. 6. The peak levels of the broadband component are in the range 22 to 35 dB at forte level and 13 to 28 dB at mezzo-forte level. There is a tendency that the peak levels are higher the shorter the distance between measured and pressed key is (this was already observed in [11] for acoustic pianos). At forte level, even the peak levels of the keys that are farthest away from the measurement positions are well above 20 dB or 10 μm (M2: 22 dB for key A7 and M3: 25 dB for key A0).

The frequency limitation mentioned in the preceding section also manifests here: there are no tonal components for keys above A4 (440 Hz) and the level of the tonal component of A0 is around 10 dB lower than for A1, A2, and A3. The tonal components of keys A1 to A3 are above the threshold for both measurement positions and dynamic levels, although the difference between the dynamic levels (2-3 dB) disappears with regard to the just-noticeable difference (JND) in configuration M3. Geischeider et al. [14] reported a JND between 0.8 and 2.5 dB for sinusoidal signals.

Summarizing, the tonal component of piano keys in the note range from A1 to A3 played with the left hand are perceivable at the right hand position. The dynamic playing level of notes played with the left hand might not be distinguishable from sensations with the right hand. However, the difference is noticeable at the left hand position and could be used for precise dynamic control of the left hand fingers themselves.

C. Influence of the Finger on Piano Key Vibrations

In the following, we demonstrate how the finger influences the vibration behavior of a piano key by inspecting the vibrations during different stages of a keystroke. The expectation is that the finger influences the vibrations of the keys because of the load increase during key depression. Also the contact points of the key to the keyframe change, when the key is fully pressed down.

As explained in [10] the piano key can be modeled as a vibrating bar with two free ends. One end is loaded by the hammer action and the other end is loaded with the force applied by the finger pressing the key. When the key is fully depressed, the boundary condition of the playing end of the key changes to a hinged-like or even clamped-like condition. A change of boundary conditions affects the acoustic modes of the key and therefore an influence on the piano key vibrations is expected.

The measurements on piano key D3 for four different conditions are shown in Fig. 7. The different conditions correspond to different stages of a key press. We observed similar results for all played keys at both dynamic playing levels and with both kinds of touch. Apparently, the change in the tonal part is only pronounced for played notes with components in the concerned frequency band. For this reason we used the results of piano key A1 (55 Hz) in Fig. 7.

As illustrated in the time signal and spectrogram in Fig. 7 the finger influences the level, the envelope and the spectral content of the piano key vibrations.

There is not much difference between conditions I1 and I2. By comparing condition I1 and I2 to I0, we observe a substantial level increase in the frequency band from 200 to 300 Hz. The reason is likely the more rigid connection of the key to the keyframe at the support point due to the load increase on the key during these conditions. By analyzing the result of condition I3, the response of the piano key in the frequency band from 200 to 300 Hz is weaker but another resonance between 100 and 200 Hz becomes most pronounced. This shift and other changes in the spectral weighting are due to the change of the boundary condition as explained above.

The higher levels in all conditions where the finger is present underlines the perceptivity of the vibrations, even tough the levels are close to the detection thresholds. Especially in conditions I1 and I2, the substantial increase has an impact, because it is within the frequency band, where the sensitivity of the fingertip to vibrations is highest (200 to 300 Hz) [5].

IV. CONCLUSION AND OUTLOOK

In this evaluation of the vibrotactile feedback rendering system of the AvantGrand N3X piano, we showed that the vibration levels on the piano keys are comparable to those measured on an acoustic grand piano. However, we observed differences in the tonal component of the vibrations for frequencies outside the band from 150 to 400 Hz, due to limitations of the TRS. The measured broadband components are like those of an acoustic grand piano but due to the mechanical generation, they can not be turned on and off with this instrument.

Further, we showed that the vibrations generated with piano keys in the range from A1 to A3 are above the detection threshold for measurement positions at the left and right hand position, although small differences in the dynamic level can only be sensed at positions that are close to the pressed key. Finally, we analyzed the influence of the finger on the vibrations. We showed that the finger touching the key has an impact on the level and the spectral weighting and explained the changes during the different stages of a key press.

Concluding, the Yamaha AvantGrand N3X is suited to study the influence of vibrotactile feedback in piano playing, if the experiments are carefully designed to circumvent the limitations of the TRS. The next steps involve a precise analysis of the timing and latency properties of the acoustic and vibrotactile feedback rendering system, before the influence of vibrotactile feedback on timing and dynamics in piano playing can be studied with this instrument.

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