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OBSERVATIONS ON THE TRANSIENT COMPONENTS OF THE PIANO TONE*

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ABSTRACT

The onset of the piano tone shows interesting characteristics due to several effects. At the very beginning of a note, a variety of transients are mixed, some of which are propagated via the strings, and others via the structure of the instrument. The details of the structure-born transients in a grand piano were studied by removing the strings for a note in the mid range and letting the hammer strike a dummy mass. It was found that structure-born transients occur at the bridge both before and after that the first transversal wave on the string has arrived ("precursors" and "postcursors," respectively). The precursors are affected by the way the key is depressed, and may thus be connected with the pianist's "touch." Both pre- and postcursors include strong components originating from resonances in the key and keybed.

INTRODUCTION

As well known, the piano tone contains a characteristic attack component, which is mixed with the sound of the string vibrations. When separating the two by using a detector for the string motion, and a microphone for the total radiated sound, respectively, the "attack-thump" can be clearly heard. This acoustic signature of the piano has caused problems when synthesising piano tones by physical modeling (Chaigne & Askenfelt, 1992), which motivated a closer look at the origin of these attack components. After doing so, we may understand clearer than before why the commercial synthesiser manufacturers still rely on the sampling technique for producing realistic piano sounds.

The attack-components are to the percussive-like excitation mechanism, which excite resonances in different parts of the piano, the most prominent being the soundboard, keybed, and rim. The excitation force can be transmitted via two major paths (Fig. 1).

1) STRING. The blow of the hammer on the string is transmitted almost instantly to the bridge and soundboard by longitudinal string propagation.

2) STRUCTURE. The accelerating force on the key, and later, the reaction force on the hammer at the blow, followed by the retardation force when the hammer is checked, are all transmitted down into the keybed and further to the rim and other parts of the structure.

Naturally, the vibrations in the soundboard, originally excited via the strings will soon spread to the rim and keybed and vice versa, and an exchange occur.

In order to study the relation between the two transmission paths, an experiment was conducted on a grand piano (Steinway C, 7½-fl.), in which the hammer first struck the strings in normal fashion, and then a dummy mass (4 kg), which replaced the strings. The facing of the dummy was covered with a thin layer of rubber in order to give approximately the same contact time as with the strings.

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String precursor - touch precursor

With the strings in place, the bridge was set in motion almost immediately after string contact (see Fig. 2). A typical delay in the mid range was 0.2 ms.

This string precursor, which precedes the first transversal wave with several milliseconds, is caused by longitudinal string motion, reflecting back and forth between the bridge and the hammer. The propagation velocity of the longitudinal motion is at least
an order of magnitude higher than that of the transversal waves. The phenomenon was foreseen by Yanagisawa et al. (1977), and observed by Podlesak and Lee (1988). The amplitude of the string precursor when observing the bridge acceleration was typically between 1/3 - 1/5 of the transversal wave (-9 to -14 dB). This precursor, which lasts for only 1 - 2 ms (mid range), is not affected by touch.

After replacing the string triplet with the dummy mass, and increasing the sensitivity by a factor 20, an interesting picture emerges (see Fig. 3). The bridge is seen to move before, as well as after, the blow by the hammer on the dummy. The existence of an initial sound before string (or dummy) contact has been known since long among piano people (see e.g. Rimsky-Korsakov, 1952), often referred to as "touch noise" in the following touch precursor. More recently, it was observed by Boutillon (1988). The touch precursor is naturally much weaker than the string precursor, typically 25 dB below, but more interestingly, it is dependent on touch.

For a "staccato"-type of touch as in Fig. 3, in which the key is struck by a relaxed finger from some distance above, the touch precursor lasts for about 20 - 30 ms. During this part, the bridge motion is dominated by resonances at about 290 and 440 Hz. Surprisingly enough, these components were traced to resonances in the key. For a "strained" touch, in which the key is forced down with a stiff finger in an un-pianistic way, the touch precursor is very much reduced. In a "legato-touch", where the key is pressed down smoothly with the finger initially resting on the key, no touch precursor is observed at all.

The history of the bridge motion after the hammer has struck the strings is normally dominated by the string vibrations, which mask the structure-borne vibrations entirely. With the dummy, however, an episode of relatively strong and rapid oscillations at about 900 Hz can be observed immediately after dummy contact, followed by a mix-
ture of 100 and 250 Hz. These three components are due to resonances in the key, soundboard and keybed, as will be discussed below. A little surprisingly, also this part of the touch process is somewhat dependent on the type of touch, with the staccato giving most low-frequency ringing from soundboard and keybed.

Both pre- and postcursors are weak. The vibration level at the bridge for a mezzo forte blow on the dummy is compatible with pianissimo level in normal playing. Whether or not listeners can discriminate between different types of touch by the nature of the precursor remains to be studied in carefully designed listening test. Perceptual studies of onset asynchrony, in particular cases in which a weak sound precedes a much stronger sound, suggest that at least the prominent touch precursor in a staccato-touch (approximately 30 - 40 dB below the transversal wave) would be detectable (Rasch 1978).

**Transmission strings - structure**

Returning to the transmission of the attack components along different paths we can compare the spectra of the bridge vibrations for three cases; (1) with dummy, (2) with damped strings, and (3) the normal case with undamped strings.

![Fig. 4. Spectra of the bridge vibrations for three cases; with strings (broad line), with strings but transversal string motion damped (thin line), and with dummy (shaded), staccato, C4.](image)

The dummy-spectrum, which extends up to only 2 kHz, shows a level about 40 dB below the string partials. These are the vibration components transmitted via the structure of the piano. In comparison, consider the second case, in which the strings are installed, but where the transversal string vibrations have been damped (while letting the longitudinal components pass on to the bridge). This damped-string case, which contains the relatively strong string precursor mentioned earlier, shows a spectral level which generally is about 25 dB higher than for the dummy case, and it also extends considerably higher in frequency, in fact up to about 5 kHz.

The transmission via the longitudinal string precursor is thus the major path for the attack sounds, at least above 1 kHz, while the transmission via the structure of the piano seems to contribute only at lower frequencies. Very simplified, we could say that the string transmission gives the "bite" in the attack of the piano tone, while the structure adds low frequency "thump." Together they define a "noise floor" in the bridge spectra.

Looking at the radiated sound, essentially the same relations are seen as in the bridge vibrations, however, with the string partials a little less dominating. This indi-
cates that other surfaces than the bridge, e.g. the rim and keybed, also radiates the background level. We could thus expect more low-frequency "thump" in the radiated sound than in the bridge vibrations. In particular, this was found to be the case for the touch precursor in the staccato-touch (see Fig. 5).

![Graphs showing vibrations and radiated sound](image)

*Fig. 5. Comparison of the vibrations at the bridge (top) and keybed (middle) in relation to the radiated sound (bottom) during the touch precursor in a staccato-touch. The bridge acceleration and radiated sound have been normalised by setting the "steady-state" portions (the "over-loaded" parts to the right) to equal amplitude before magnifying the signals (staccato, C4).*

This figure compares the vibrations in the bridge and keybed with the radiated sound. The amplitude scales have been normalised by setting the "steady state" part of the bridge acceleration and radiated sound, respectively, to the same amplitude before magnifying the waveforms. It is seen that the precursory component is much stronger in the keybed than in the bridge vibrations, and that the radiated sound is strongly influenced by the low-frequency keybed components. This observation tallies with the common knowledge among piano technicians, that the stiffness of the felt washers under the keys can influence the attack sound noticeably.
Prominent resonances

Some of the prominent resonances observed in the bridge vibrations were studied separately. In the staccato-touch, two components at 290 and 440 Hz dominated the bridge motion during the acceleration of the key (see Fig. 3). These resonances were traced to the key, both modes resembling the first mode of a free-free bar with a node approximately at the position of the capstan screw and a large motion at the pivoting point on the balance rail (see Fig. 6). The mode shapes suggest that the force against the supporting balance rail is temporarily relieved as soon as the sudden impact has been delivered in a staccato-touch. The existence of two modes with seemingly similar modal shapes, occurring at different frequencies, is of course intriguing, but the higher mode may well be a combination of bending and torsional motion.

Fig. 6. Principal shapes of the normal modes of a key of a grand piano (freely supported) at 290 and 445 Hz (top), and 914 Hz (bottom). The excitation force during touch acceleration is indicated by an arrow.

After the impact, a "wave package" was seen in the bridge vibrations at about 900 Hz, superimposed on the lower resonances (see Fig. 3). This later component was caused by a higher key resonance (second mode for a free-free bar), with a node at the midpoint corresponding to the pivoting point. This mode seems to be excited by the sudden retardation of the key at bottom contact at the end of the touch. The oscillation is terminated as the rebounding hammer is captured by the back check (at the inner end
of the key). This occurs approximately 10 - 20 ms after dummy contact. Interestingly, the rebounding hammer itself vibrates vividly at a frequency of about 900 Hz when being checked (Askenfelt & Jansson, 1991).

Other strong resonances in the instrument can also be observed in the bridge vibration spectra, for example the soundboard (100 Hz), keybed (95 and 330 Hz), and rim (250 Hz). Also the bars in the metal plate, all of different length and cross section, show distinctive resonances at a number of frequencies. A low resonance at 38 Hz, present in the vibrations at all measuring positions, was interpreted as a fundamental resonance in the structure, formed by the heavy metal plate resting on the open bars of the wooden fundament.

It was noticed that many of the modes in the instrument fall very close in frequency. Whether or not this is the result of a careful design, or if just happened to turn out this way, is an interesting question. In any case, the manufacturers are well aware of the importance of the structure-borne attack components. For example, the recognised piano makers select the wood for the keybed with great care, as they do with the wood for the soundboard.

CONCLUSIONS

The experiments have shown that the dominating part of the attack sound is transmitted longitudinally via the strings by the string precursor. This component is short, about 1 - 2 ms, but only 10 dB weaker than the first transversal wave. The string precursor is independent of touch.

Structure-borne pre- and postcursors add low-frequency in the radiated sound. These components, which are touch-dependent, are about 25 dB weaker than the string precursor. On the other hand, they operate on a much longer time scale, starting 20 - 30 ms before string contact for an impulse-like type of touch (staccato). A little surprisingly, prominent resonances in the key dominate the pre-contact history of the bridge motion when applying a staccato-type of touch. After contact, a second key resonance at 900 Hz add, followed by contributions from the keybed and soundboard at 100 and 250 Hz, respectively. These post-contact components are less dependent of touch. The perceptual implications of the pre- and post cursors, and their possible connections with the touch of professional pianists, remain to be studied.

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