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VIBRATIONS OF PIANO STRINGS AND COUPLING TO THE SOUNDBOARD

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In this paper we give a brief account of some measurements of the resonant and transient response of strings on a piano. From such measurements we can derive quantitative information on the strength and nature of the coupling between the vibrating strings and the soundboard at the supporting bridge. This also provides valuable information on the characteristic vibrational response of the soundboard, which must play an important role in determining the tone of a particular instrument, but about which remarkably little information appears to have been published.

It is well known that sound from a well-tuned piano can persist for very long times after the initial transients have died away. Hundley et al [1] argue that this is not caused by a faster decay rate of the upper partials excited but is produced by the slight mistuning of the string doublets and triplets. When a triplet is excited by the hammer in the normal way, all three strings are initially forced to vibrate with equal amplitude. The resulting induced motion of the bridge leads to a decay rate three times faster than that of a single string vibrating alone. These authors argue that the slight mistuning leads to a dephasing of the individual string vibrations, resulting in a decreased force on the bridge and a diminished, but time-varying decay rate at long times.

Weinreich [2] argues that the problem should be considered self-consistently by describing the vibrations in terms of the normal modes of the string doublets and triplets coupled via their mutual interaction with the soundboard. For a doublet, the modes can be represented as (↑↑) and (↑↓), where the arrows indicate the amplitude and phase of the associated string vibrations. For identically tuned strings, these amplitudes are equal, but in general the amplitudes differ by an amount that depends on the degree of mistuning and on the strength and nature of the coupling. The normal hammer action will excite the (↑↑) very strongly, but with a small (↑↓) component, which will always dominate at sufficiently long times, since it has the slower decay rate, for the reasons outlined above. A secondary aim of this investigation was to verify the existence of these weakly damped modes and to assess their likely importance in practice.

From our previous studies of vibrating strings on the violin and cello [3], we expect individual strings to support two distinct modes of transverse vibration. To a good approximation, these modes will be polarised in directions nearly parallel and perpendicular to the motion of the string on the bridge associated with the coupling to the soundboard. In practice, these directions are generally not strictly parallel and perpendicular to the plane of the soundboard, as might have been expected for coupling to the predominantly flexural vibrations of the soundboard (see also refs. 1 and 2). Presumably, the bridge is involved in a rocking action not dissimilar to that observed on the violin, though the possibility of coupling to longitudinal vibrations of the soundboard at the higher frequencies has not yet been ruled out. For convenience, we refer to the more strongly coupled mode of string vibration as the "coupled" mode and the less strongly coupled mode as the "uncoupled" mode, even though the latter may be weakly coupled and thus be responsible for some of the radiated sound.

String vibrations are monitored at a chosen angle relative to the plane of the soundboard using a matched infra-red LED and photo-diode with an electronic detection system incorporating a phase-sensitive detector (PSD), as described in an accompanying paper [3]. For transient measurements, the reference signal for the PSD is set at a slightly lower frequency than the fundamental frequency at which the string vibrates. As the phase of the string vibrations alternates with that of the reference, the output of the PSD, plotted as a function of time on an xy-recorder, gives a trace with a beat frequency determined by the fundamental frequency of string vibration and an envelope which describes the characteristic decay of string vibrations.

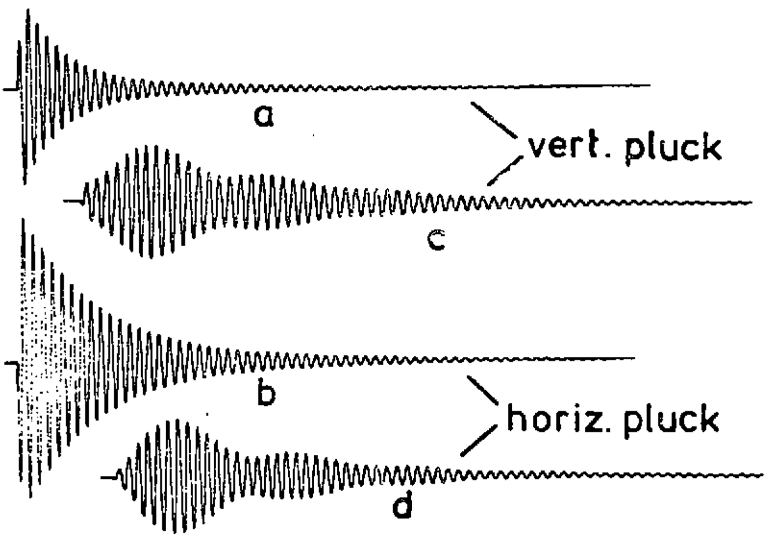

Fig.1 Transient measurements on a single string; in isolation (a) and (b), and in combination with a second plucked string forming a doublet (c) and (d).

Fig.1 shows typical xy-recorder traces for the transient response of a single string (A^b below middle-C) measured at about 45° to the plane of the soundboard. Figs.1a and 1b illustrate the different decay rates for the "coupled" and "uncoupled" modes of string vibration principally excited when the string is gently plucked in the vertical and horizontal directions respectively. These measurements were made with all other strings damped or inhibited from vibration using rubber wedges. Figs.1c and 1d illustrate the transient response of the same string but with one of the other strings of the parent triplet released and gently plucked in the vertical and horizontal directions. The beat pattern demonstrates the expected interchange of energy between the coupled strings, which, following Weinreich [2], we interpret as the interference of the (↑↑) and (↑↓) modes, the latter mode having the expected slower decay rate. The significant excitation of these modes when the string is plucked in the horizontal direction shows that the coupling to the soundboard cannot be strictly perpendicular to the plane of the soundboard.

From such measurements it is relatively straightforward to determine the damping and difference in frequency of the "coupled" and "uncoupled" modes of string vibration, to estimate the direction of coupling at the bridge, and to study the influence of this coupling on the normal modes of the coupled system of string doublets and triplets. Knowing the mass of the string, measurements of the damping and frequency shifts caused by the coupling enables the real and imaginary components of the complex terminating impedance at the bridge to be determined, as described in the accompanying paper [3].

Transient measurements were made at semi-tone intervals for most strings in the lower half of the keyboard-range. Given a sufficiently fast transient recorder, this technique could have been extended to all the strings. However, for the upper half of the keyboard range, measurements were made using the resonance technique [3]. A given string was excited electromagnetically by passing a sinusoidally varying current through the string, with a rigidly mounted magnet placed nearby to produce an exciting Lorentz force on the string, in a direction determined by the string-magnet geometry. The vibrations of the excited string, or of another string of the parent doublet or triplet, was monitored using the photo-detector system described above. For such measurements, the reference for the PSD was derived from the current passing through the string, so that the response of the string could be monitored as the excitation was slowly swept through the region of resonance. Both the component of induced velocity in-phase with the exciting force and at 90^0-phase was given by the PSD and was plotted on the xy-recorder. The width of the resulting resonance curves at half-height is equal to $2.19/\tau_{60db}$, where τ_{60db} is the 60db decay time that would have been obtained from measurements of the transient response.

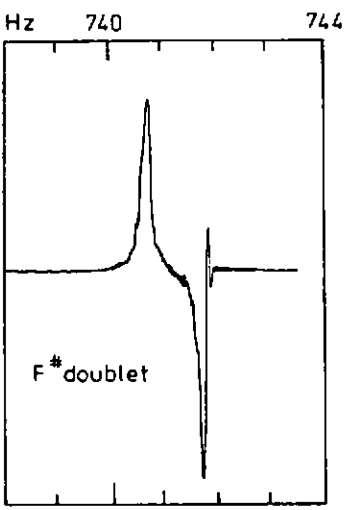

Fig.2 Resonance of a string doublet

Fig.2 shows an example of such a measurement for two strings of the F# triplet an octave and a half above middle-C. The response of the centre string is monitored while the left-hand string is excited, the right-hand string being wedged. The coupling causes the monitored string to vibrate as a component of (↑↑) and (↑↓) modes. The additional ringing on the upper, inverted resonance curve shows again that the (↑↓) mode is less strongly damped, as predicted by Weinreich [2].

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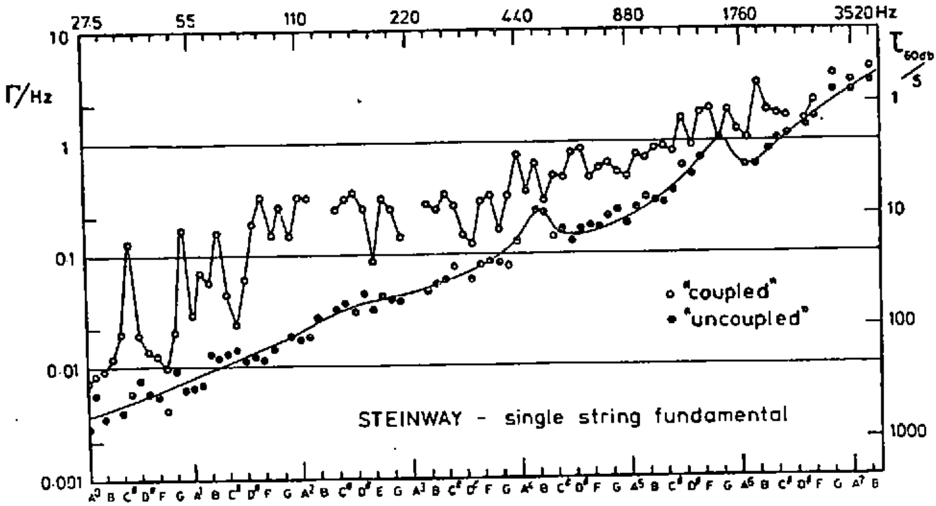

Fig.3 Width and decay time for "coupled" and "uncoupled" modes of single string

The values plotted above for the width of the "coupled" and "uncoupled" resonances were obtained from transient and resonance measurements made on single strings. Measurements of the difference in frequencies of these modes were both positive and negative and were comparable in magnitude to the width of the "coupled" resonances, showing that the real and imaginary components of the terminating impedance are comparable, as anticipated. We note the fairly uniform increase in damping of the "uncoupled" mode with increasing frequency, with just a suspicion of additional damping at ≈ 500 and 1500 Hz, which could be associated with acoustically radiating, longitudinal resonances of the soundboard. The sharp peak in the damping of the "coupled" resonance near D in the lowest octave can almost certainly be associated with the lowest acoustically important soundboard resonance. Measurements at less than semi-tone resolution will be necessary to make unambiguous identification of sound-board resonances at higher frequencies. We anticipate making such measurements on a number of pianos in an attempt to correlate the information thus obtained with the quality of the instruments studied.

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References

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