Some notes on the clavichord

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Various acoustical features of the fretted clavichord, in some ways the simplest of keyboard instruments, are investigated experimentally and theoretically. The unusual excitation mechanism, in which a metal blade strikes the string and holds it deflected, yields an excitation force spectrum level with a smooth slope of 6 dB/oct, though the radiated spectrum depends greatly on the properties of the soundboard. Energy loss from the paired strings occurs primarily through the bridge to the soundboard, interaction between the strings giving a two-stage decay as described by Weinreich [J. Acoust. Soc. Am. 62, 1474–1484(1977)]. The uncomplicated soundboard configuration allows its measured response from 50 to 1000 Hz to be well accounted for theoretically. In this important range, a series of couplings between normal modes of the soundboard and of the enclosed air cavity considerably modifies the system response. The sound pressure level and sound decay time to inaudibility across the compass of the instrument are consistent with the string and soundboard behavior.

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INTRODUCTION

According to Sachs[1] the forerunner to the clavichord first appeared in the twelfth century and developed from an attempt to excite a monochord with a keyboard. By the end of the fourteenth century this instrument had developed into one having some eight strings, tuned in unison, and a system of metal blades or "tangents" on the ends of keys adjusted to strike the strings at various lengths to give a compass of more than two octaves. In the early fifteenth century this new instrument was named "clavichord," from "clavis," a key, and "chorda," a string, and by the mid-sixteenth century it had developed almost to its modern form. The earliest clavichord still in existence, dated 1534, is very similar in its design to the now established fretted clavichord.

Although, in the eighteenth century, unfretted clavichords were built, the fretted or "gebunden" design, in which several adjacent notes use the same pair of strings, has for a number of reasons remained the most popular. The authors' instrument is a fairly typical example, being designed by Zuckerman after one built in Germany in the late seventeenth century. It has 20 string pairs of different length, cross-sectional area and tension, and is fretted to achieve a compass of four octaves, the lowest octave being a "short" octave with several missing notes. It thus has 45 keys. The principal features of the layout of the instrument are shown in Fig. 1 where the long dimension measures 1 m. As can be seen, it is quite small enough to be easily carried, one advantage of being fretted, and this probably explains the popularity it once enjoyed. Because the clavichord is very quiet, the trend towards louder music and more noisy environments in the last 100 years had caused it to fade from the musical scene, but the present popularity of older music has renewed interest in it.

I. THE STRINGS AND KEYS

As shown in Fig. 1, the strings of the clavichord run the length of the instrument from the hitch pins at the bass end, or back, across the bridge by bridge pins, to be wound around the tuning pins at the treble end. The keys are perpendicular to the long dimension and are adjusted with respect to their geometries so that the tangents are placed at the appropriate intervals along the strings. The keys are all pivoted on pins on the balance rail and are caused to run without swiveling by the "thumb nails" which travel in grooves in the guide rail along the back of the case. When a key is depressed the brass tangent rises to strike the appropriate string pair and, so long as it is held against the string, the distance from the tangent to the bridge defines the sounding length. The remaining part of the string is damped with felt. The key and tangent return to their rest position under the influence of gravity.

There are three adjacent keys to each string pair for the 9th–19th pair, two for the 7th and 8th pairs in the bass and the 20th pair in the treble, and one key to a pair for the lowest four notes. All the strings are brass and the string schedule is shown in Table I. Each pair is tuned in unison, the presence of two strings causing increased loudness and a longer decay time, as discussed later. The length scaling is "proportional" from C_6, which is the top note, down to D_4. This means that the string length is doubled for each octave descending the scale. Below this, in place of doubling the string lengths for octaves, shorter strings of greater cross-sectional area are used. The string tension therefore does not become unduly low in the

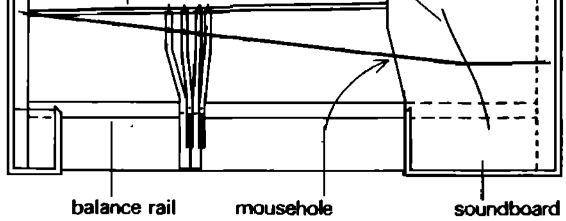

FIG. 1. Plan of the clavichord showing the main structural features. The strings shown are the 10th pair; there are 20 pairs in all. The overall length of the instrument is 1 m.

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TABLE I. String schedule for this clavichord. (The unusual progression is due to the "short octave" in the bass.)

Pin pair	Notes	Wire diameter (mm)
1	C_2	0.63
2	F_2	0.56
3	D_2	0.56
4	G_2	0.51
5	E_2	0.56
6–7	A_2–B_2	0.46
8–9	C_3–E_3	0.41
10	F_3–G_3	0.36
11–12	$G\#_3$–$C\#_4$	0.33
13	D_4–E_4	0.30
14–20	F_4–C_6	0.28

bass. The instrument is commonly tuned a whole tone above normal modern pitch which is $A_4 = 440$ Hz. This tuning is prompted by the extremely short "scale" of the instrument. The "scale" is expressed in terms of the length of the C_5 string, which is usually 26–35 cm ($10\frac{1}{2}$ to 14 in. in the builder's terminology), but for this clavichord it is only about 21 cm ($8\frac{1}{2}$ in.). For this scale, modern pitch leaves some of the lower strings a little too slack.

It soon became evident in our studies that the player, in striking a key, makes up for the simplicity of the key mechanism by the complexity of the human servomechanism involved in the "touch." The tangent rises about 3 mm to strike the string and a further 1–2 mm in deflecting the string. Although the tension is quite small, it is the "feel" of this string reaction which causes the player to stop the key. For this reason, to build a mechanical key player was judged too difficult.

Figure 2 shows the variation of the tangent velocity during the striking of a note, in this case C_4. This was measured by observing the voltage generated in a small length of wire glued to the key near the tangent and moving in the field of a small magnet. It can be seen that the tangent accelerates from rest and then, after striking the string, decelerates towards rest in a displaced position. When in contact with the string, however, it also suffers small oscillations caused by the string vibration. The velocity v_0 of the tangent at the moment of striking the string is about 0.5 ms^{-1} and it is brought substantially to rest after about 20 ms, corresponding to about four complete oscillations at the fundamental frequency of the string.

At the same time that this measurement was being made, a measurement was also made of electrical contact between the tangent and string, as shown in the lower part of the figure. The case shown is typical and exhibits no sign of contact bounce, contrary to the view of Benade.[2] Occasionally such bouncing does occur and is more likely on some notes than others, but the bounce generally occurs some 15–20 ms after initial contact, corresponding to a natural resonance of the key-string-finger mechanism, and produces a "dead" and unsatisfactory sound.

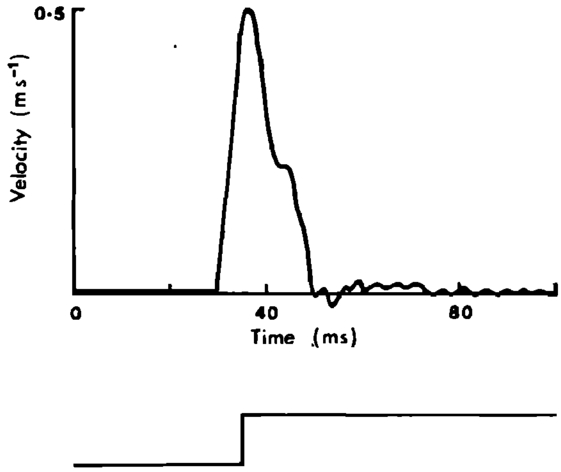

FIG. 2. Oscillograph trace of tangent velocity during the striking of a string. The lower trace measures the electrical contact between the tangent and the string.

The excitation mechanism in the clavichord is quite different to that of other keyboard instruments such as the piano or harpsichord in that, rather than the string being struck or plucked, one of its ends is abruptly displaced through a small distance and then held. The time scale of the displacement is, however, generally relatively long compared with the travel time of a wave along the string.

In order to analyze this situation approximately, it is convenient to assume that the tangent velocity v decreases exponentially towards zero after contact with the string. Figure 2 shows this to be a reasonable but by no means exact approximation. If the string were of infinite length then we might write the tangent velocity as

$$v(0,t) = v_0 \exp(-\alpha t), \tag{1}$$

where α is a factor measuring the initial rate of deceleration. This would then give a wave on the string with displacement of the form

$$y(x,t) = (v_0/\alpha)[1 - \exp\alpha(x/c - t)], \tag{2}$$

for $x < ct$, where c is the wave velocity on the string.

In fact this wave is folded back upon itself by reflections at the string ends, the sign of y being changed at each reflection. The particular form chosen to approximate the tangent velocity, however, makes evaluation of this resultant displacement relatively straightforward and its form is particularly simple if the time t is chosen as an integral number of wave transit times along the string, so that the leading edge of the initial wave has just reached one end. It is also useful to refer the displacement and velocity to the final displaced position of the string from the bridge to the tangent. The resulting displacement and velocity are then given in the limit of long times by

$$y(x) = \frac{v_0}{\alpha}\left(1 - \frac{x}{L}\right) + \frac{v_0}{\alpha}\left[e^{\alpha x/c}\left(\frac{e^{-2\alpha L/c}}{1 - e^{-2\alpha L/c}}\right) - e^{-\alpha x/c}\left(\frac{1}{1 - e^{-2\alpha L/c}}\right)\right] \tag{3}$$

and

$$v(x)=v_0\left[e^{-\alpha x/c}\frac{1}{1-e^{-2\alpha L/c}}-e^{\alpha x/c}\frac{e^{-2\alpha L/c}}{1-e^{-2\alpha L/c}}\right], \quad (4)$$

where L is the string length.

For our present purposes we are concerned only with the spectrum of the force on the bridge, the phase information being irrelevant. We may therefore make a Fourier analysis of the string motion at the instant giving the results (3) and (4) and then evaluate the Fourier components of the force on the bridge from the relation

$$F=T(dy/dx)_{x=L}, \quad (5)$$

where T is the tension.

If the string motion is specified by

$$y(x,t)=\sum_n \sin(n\pi x/L)[A_n\cos(n\pi ct/L)+B_n\sin(n\pi ct/L)], \quad (6)$$

where $t=0$ is now the instant at which the configuration is as in (3) and (4), then we find

$$A_n=2v_0/n\pi\alpha-2v_0 n\pi/\alpha L^2D, \quad (7)$$

$$B_n=2v_0/cLD, \quad (8)$$

where

$$D=(\alpha/c)^2+(n\pi/L)^2. \quad (9)$$

The Fourier components of the bridge force are then given by

$$F_n=(n\pi/L)(A_n^2+B_n^2)^{1/2}, \quad (10)$$

When the coefficient α is small relative to $\pi c/L$, so that the tangent decelerates over several periods of the fundamental of the string oscillation as is the case for all except the lowest strings of the clavichord, then $A_n \ll B_n$ and the force components F_n vary very nearly as $1/n$. If α is larger (or c/L smaller) then the amplitudes of the lowest few harmonics of F_n are more nearly constant with the $1/n$ behavior taking over at higher frequencies. This excitation force spectrum is, of course, greatly modified by the resonance and radiation properties of the soundboard and so bears no very direct relation to the radiated sound spectrum. It is not sensitive to the exact form assumed for $v(0,t)$ in (1). The two cases for α are shown in Fig. 3.

The form of the decay of the vibration amplitude was also measured for C_4. This was done for the string pair and on a single string, the other string being held aside. A microphone positioned above the soundboard was used to record the notes on tape and these were subsequently analyzed using an oscilloscope.

For the single string the decay in amplitude was exponential with the decay time τ varying somewhat depending upon how heavily the note was struck. The measured decay times ranged between 0.27–0.36 s. When the string pair was used the form of the total decay was no longer simply exponential. Instead there was an initial period of decay faster than the single-string case and then a subsequent period where the decay time was very long. The initial fast decay section had a measured decay time between 0.15–0.19 s or approximately half the single-string time. As a consequence of this two-stage decay the notes played on the string pairs are subjectively much more sustained than the notes on a single string.

This observation suggests that the two strings are interacting through the bridge according to the theory of Weinreich[3] developed for piano strings. For a purely real bridge admittance the vibration of a pair of strings tuned in unison can be described as consisting of a combination of a symmetric and an antisymmetric motion. (If there is any mistuning of the strings then the normal modes of the pair deviate accordingly from the exactly symmetric and antisymmetric motions.) When the strings are struck by the tangent in such a way that they vibrate in phase with identical amplitudes then the motion is purely symmetric and the string amplitudes will decay at a rate equal to twice the single-string rate due to the doubling of the force on the bridge. In the real situation the irregularities in the tangent introduce some of the antisymmetric mode into the vibration. The symmetric part still decays at twice the single string rate but the antisymmetric part ideally decays only due to losses other than those across the bridge. Of course, exact unison of tuning can never be achieved in the clavichord and the soundboard admittance is certainly not purely resistive. This latter fact causes a frequency difference between the normal modes which then beat against each other.

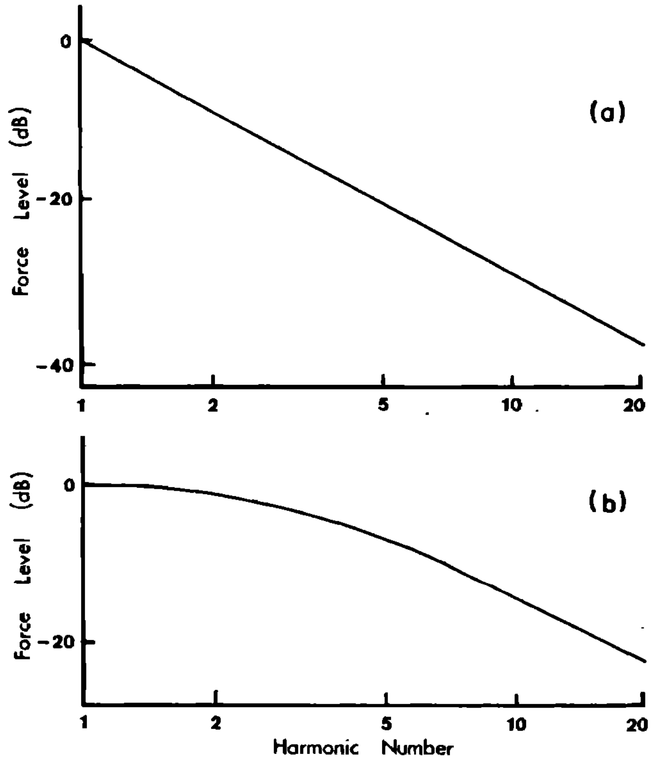

FIG. 3. Variation in the level of the spectral components of the force on the bridge, F_n, with respect to the fundamental for (a) the C_4 string pair (a curve almost identical to this obtains over the entire clavichord compass), and for (b) the decay parameter α equal to ten times the value used in (a).

In order to calculate the decay time corresponding to energy losses to the soundboard, it is necessary to know the real part of the soundboard admittance at the appropriate bridge-pin pair. Since only the magnitude of the admittance, Y, could be measured, only a lower limit to this time could be calculated. Referring only to the energy contained in the fundamental, the calculated decay time is approximately 0.19 s.

The rate of energy loss from the strings depends not only on losses to the soundboard but also on viscous losses to the air, internal losses in the string, and also losses at the tangent. The internal losses are very small for a plain brass string. The decay time of the vibration amplitude due to viscous losses may be easily calculated from the work of Stokes[4] and is approximately 3.6 s. This is evidently not an important loss mechanism in this case.

The remaining sources of energy loss are at the end of the string passing over the tangent. The velocity of the tangent tip at the string fundamental can be estimated from Fig. 2 and is approximately 1 cm s^{-1}. However, the corresponding admittance, Y_T, of the tangent at the string fundamental is largely imaginary and in fact masslike since this frequency is a great deal higher than the resonant frequency, f_0, of the string-finger-key system. This frequency can be estimated from the mass and dimensions of the key and the tension of the strings and is about 10 Hz. The Q factor of the resonance is small because of the properties of the finger tip and can be estimated from Fig. 2 to be between 0.5 and 1. At the string frequency f we can write, for $f \gg f_0$,

$$\mathrm{Re}(Y_T) \simeq Y_T f_0 / Qf, \tag{11}$$

and from this we can estimate the energy loss to the tangent and the associated decay time which is approximately 1 s.

We should also consider the loss of energy along the felt-damped part of the string. If there is no reflection from the damped end, then all the wave energy associated with the tangent motion is absorbed. The amplitude of this wave, from Fig. 2, is only about 5% of that of the wave on the main part of the string so that the rate of energy loss is small and the decay time from this cause can be estimated to be about 2 s.

Combining all these sources of energy loss we estimate a decay time $\tau \approx 0.15$ s for the string pair, which is in satisfactory agreement with experiment. We conclude that loss through the bridge to the soundboard is the main damping mechanism for the strings of the clavichord.

II. THE SOUNDBOARD

The soundboard of the clavichord is fairly small and almost rectangular in shape. It is evenly 2–3 mm thick, unstrutted, and clamped firmly on all its edges The wood is chosen for its low density ($\simeq$400 kg m^{-3}) and its stiffness. The best soundboards are made from quarter-sawn sitka spruce which is then cut along the grain in strips about 10 cm wide and, every second strip having been turned over, reglued into a board. The grain runs along the long axis of the clavichord, the stiffness in this direction being about 10 times the stiffness across the board. The single curved bridge is glued and pegged across the grain of the soundboard as shown in Fig. 1. The strings are stretched over the bridge, each one making an angle around a bridge pin.

The soundboard encloses a cavity of volume about 2.3×10^{-3} m^3, which opens to the main body of the instrument via the "mousehole," which is 1.4×10^{-3} m^2 in area. The balance rail continues under the soundboard, which clears it by 2 cm, to butt against the tuning pin block.

The mechanical admittance of the soundboard was measured from 50–1000 Hz at five positions along the bridge before the clavichord was strung. This was done using a driver exerting a sinusoidal force held constant in amplitude, and an accelerometer whose signal was integrated to give velocity. The mechanical admittance which is defined as the velocity divided by the force is then proportional to the velocity. The driver was clamped in turn to the 1st, 5th, 10th, 15th, and 20th pin pairs (counting from the bass end). Above 1000 Hz, separate resonances were no longer clearly detectable. Figure 4 shows the results obtained. The same system of peaks can be identified in each trace with particular peaks being weakened or enhanced from trace to trace. The slight variation in the peak positions can be attributed to the slight misalignment of the driver clamp above the pin. This causes small transverse forces which add stiffness to the response thus apparently changing the resonant frequency.

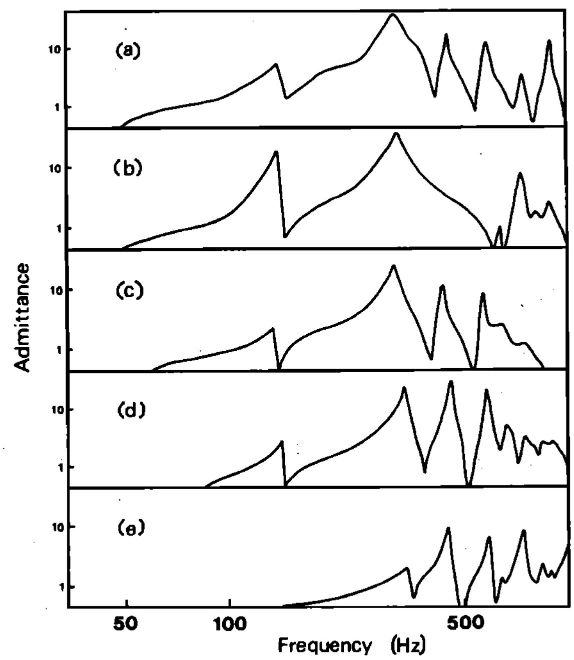

FIG. 4. Admittance of the soundboard measured at the (a) 1st, (b) 5th, (c) 10th, (d) 15th, (e) 20th bridge-pin pair. There are 20 pin pairs along the bridge, numbered from the bass, closest to the front of the instrument. The admittance is shown in units of 10^{-2} kg^{-1} s.

The plate modes were identified for the first five peaks that appear in Fig. 4. It was found that the peaks at 140 and 330 Hz correspond to the plate fundamental, the peaks at 450 and 590 Hz correspond to a mode with one nodal line, and the peaks at 760 and 870 Hz correspond to a plate mode with two nodal lines. The positions of the nodal lines for these latter two plate modes are shown in Fig. 5(a). The nodal lines for the low-frequency resonances all run parallel to the grain of the soundboard timber as a consequence of its large elastic anisotropy and the small extra stiffness contributed by the bridge.

It is clear from the results in Fig. 5(a) why some resonances are more strongly excited at some driving points along the bridge. For example, the double fundamental peaks at 140 and 330 Hz are almost completely missing when the plate is excited at the 20th (extreme treble) pin pair. This is expected in view of the fact that this pin pair lies within 20 mm of the edge of the soundboard. The peaks at 450 and 590 Hz corresponding to the second plate mode are not excited when the plate is driven at the 5th pin pair since, as can be seen in Fig. 5(a), this pin pair lies on the nodal line for this mode. However, when driven at the 15th pin pair, the soundboard responds with these peaks as strong as the fundamental.

It is evident that the splitting of these various plate resonances is due to coupling between the plate modes and resonances of the enclosed air cavity. To measure the frequencies of air modes in this cavity, the soundboard was clamped and the cavity resonances were excited using a loudspeaker held outside the mousehole. A microphone placed in the far corner of the cavity recorded maxima in its output at frequencies of 157 Hz, which is the Helmholtz resonance, and at 560 and 850 Hz, corresponding to higher modes in the cavity.

Splitting of the fundamental plate resonance has been examined in guitars and violins by a number of authors.[5-8] Often the first peak is referred to incorrectly as the Helmholtz or cavity resonance and the second as the plate resonance. The splitting arises from the coupling of the Helmholtz resonance, which appears in fact as the antiresonance, and the plate fundamental. By the use of electrical analogs the magnitude of the splitting due to this coupling can readily be calculated.

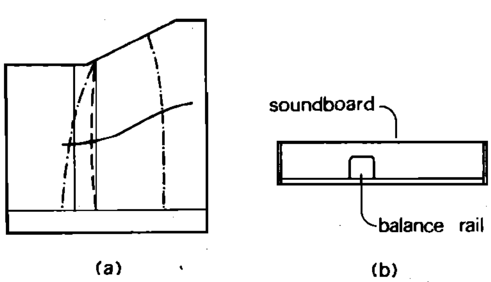

FIG. 5. (a) Plan view of the soundboard showing the node lines for the second (----) and the third (– • – • – •) plate modes. The fine lines show the positions of the balance rail and the tuning pin block. (b) Section through the cavity beneath the soundboard from front to back of the instrument, showing the position of the balance rail.

The Helmholtz resonance arises from a parallel resonant combination of the compliance of the air cavity volume C_H, and the inertance of the air plug in the mousehole, L_H. The plate is represented by a series resonant combination of a compliance, C_p, due to the plate stiffness, and inertance due to its mass, L_p. The resultant circuit is shown in Fig. 6(a). The current in the primary loop is then the acoustical volume flow if C_H, L_H, C_p, L_p are acoustic quantities.

The acoustic compliance is $C_H = V/\rho c^2$, where V is the cavity volume, ρ the air density, and c the speed of sound in air, giving $C_H \simeq 2\times10^{-8}$ kg^{-1} m^4 s^2. L_H is most easily calculated from the Helmholtz resonance frequency, f_H, since the irregular shape of the mousehole makes calculation from the dimensions difficult. Using $f_H = 157$ Hz, we find $L_H \simeq 50$ kg m^{-4}.

The mechanical inertance of the plate is simply the effective mass of the plate. To convert to acoustic inertance it is easiest to consider the plate as a simple piston and divide by its effective area squared. The effective area for air displacement was estimated to be $\sim\frac{1}{3}$ of the plate area (considered as a simple piston) and this gives $L_p \simeq 220$ kg m^{-4}. Assuming a fundamental plate resonance $f_0 = 300$ Hz, which is reasonable since we know it must be less than 330 Hz and greater than 157 Hz, we have $C_p \simeq 1.3 \times 10^{-9}$ kg^{-1} m^4 s^2.

The magnitudes of the resistances which appear in the circuit can be estimated from the quality factors, Q, of the resonances. Since typically $Q \sim 30$ for dry timber, the terms involving resistance are at least an order of magnitude smaller than other terms in the equation for the volume flow. They can therefore be ignored to a first approximation. This leads to infinities at the calculated resonances, but this is not im-

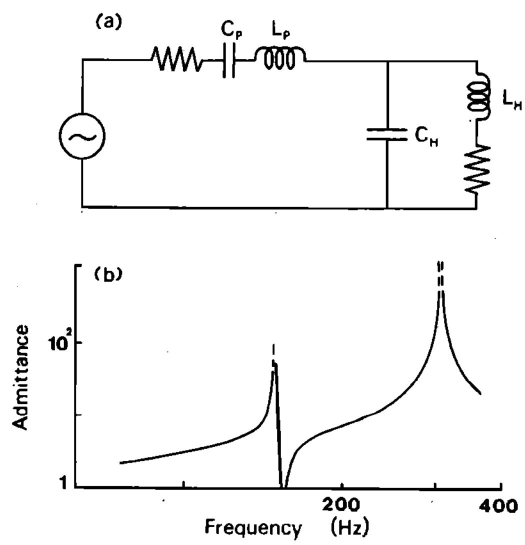

FIG. 6. (a) The electrical analog network representing the coupling between the Helmholtz resonance and the fundamental plate mode. The generator represents the mechanical force of the string on the bridge. (b) The relative magnitude of the plate admittance calculated with the circuit in (a) and the numerical values given in the text. The absolute value, which depends on driving position, is unspecified.

portant since here we are concerned only with the general form of the admittance curve.

Figure 6(b) shows the calculated volume flow in the plate loop. Evidently the plate velocity and thus the plate admittance are directly proportional to this quantity. To calculate the magnitude of any driving-point admittance, the relationship between the velocity of the effective piston and the velocity at the point in question needs to be known. This can be measured or estimated from approximate plate-mode shapes, but we shall not concern ourselves to do this here. Clearly the admittance becomes zero for a driving point exactly on a nodal line of the mode involved, and reaches a maximum approximately midway between nodal lines.

There is little doubt therefore that the peaks in Fig. 4 at 140 and 330 Hz represent coupling between the Helmholtz resonance and the fundamental plate resonance. This is exactly the same conclusion reached by those who have studied the violin and the guitar. For the 140-Hz peak, the air motion is essentially in phase with the plate motion, adding mass and lowering frequency, while for the 330-Hz peak, the air motion is in opposite phase, adding stiffness and raising the plate frequency.

As shown in Fig. 5(b), the presence of the balance rail running as a constriction through the cavity almost exactly beneath the nodal line for the second plate mode line suggests that there could be coupling between this mode and a coupled air mode involving the two halves of the cavity and having its node along the balance rail. The two peaks then correspond to the two cases where the air motion is either in phase with the movement of the two plate segments or out of phase. The first

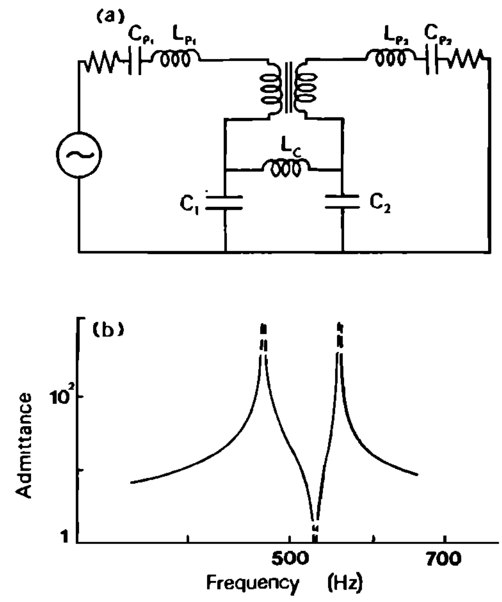

FIG. 7. (a) The electrical analog network representing the coupling between the air cavity and the second plate mode. The generator represents the mechanical force of the string on the bridge. (b) The relative magnitude admittance of the soundboard calculated by use of the circuit in (a). The absolute value which depends on the driving point is unspecified.

causes an effective mass increase of the plate which lowers its resonance, and the second an effective stiffness increase which raises the resonant frequency.

To treat the air resonance properly it is now only marginally justifiable to use a lumped-parameter electrical analog, for the system dimensions are no longer very small compared with the sound wavelength involved, but approach a quarter wavelength. For our present semiquantitative approach, however, such a simplification is justified. The electric analog network representing the system then has the form shown in Fig. 7(a). The plate is now seen as two pistons of different area, each a series resonant combination. The air mode in the cavity is shown as two Helmholtz resonators coupled through a common inductance, that is, the constriction between them. This combination appears as two capacitances and a series inductance in the figure. The transformer is necessary as a second coupling between the two plate loops because the two separate pistons are in fact parts of the same plate vibration. Each must thus be constrained not only to vibrate in antiphase with the other but also to vibrate at such an amplitude that the actual average displacements for this plate mode are reproduced. The transformer turns-ratio is therefore roughly inversely proportional to the relative areas of the two sections of the vibrating plate, and the windings are in antiphase.

The values of the impedances, $L_{P1}, C_{P1}, L_{P2}, C_{P2}$, for the two plate sections were calculated as for the fundamental with the second plate-mode frequency being assumed to be about 500 Hz. For the larger plate segment $L_{P1} \simeq 3.8 \times 10^2$ kg m^{-4} and $C_{P1} \simeq 2.7 \times 10^{-10}$ kg^{-1} m^4 s^2 and for the smaller $L_{P2} \simeq 6.3 \times 10^2$ kg m^{-4} and $C_{P2} \simeq 1.6 \times 10^{-10}$ kg^{-1} m^4 s^2. The cavity capacitances, C_1 and C_2 are easily calculated from their volumes, and the inductance, L_C of the constriction can be estimated from its dimensions. Thus we have $C_1 \simeq 1.3 \times 10^{-8}$ kg^{-1} m^4 s^2, $C_2 \simeq 5.9 \times 10^{-9}$ kg^{-1} m^2 s^2 and $L_C \simeq 20$ kg m^{-4}. The air resonance for this mode is thus at about 560 Hz which agrees with the observed resonant frequency. With these values the calculated admittance is shown in Fig. 7(b). Again the agreement with the experimental peak positions is good. Presumably the third mode of the plate can also couple in a similar way with a cavity standing wave. The balance rail still lies beneath a plate node for this mode and the air resonance at 850 Hz is at an appropriate frequency. However, there seems nothing to be gained by reiterating the calculation for this case since we are not attempting a detailed comparison with experiment. Above the third harmonic, couplings with standing waves in the cavity are too complex for this type of simple analysis.

After the clavichord has been strung and tuned to $A_4 = 440$ Hz, the series of measurements of the admittance already described was repeated. Almost no change in the pattern and heights of the peaks was observed. However, superimposed on the response was a series of narrow resonances of $Q \sim 30$ corresponding to the frequencies of the strings now woven with felt.

At approximately 670 Hz another series of much higher Q resonances appeared which modified to some extent the unstrung response near that frequency. These correspond to the portions of the strings between the bridge pins and the tuning pins, which all ring at frequencies around 670 Hz. Since these strings are undamped, their decay times are much longer than the felt-damped sounding lengths of the strings. In total these results suggest that the effect of the load imposed on the soundboard at the bridge by the string is quite small.

So we see that the frequency response of the clavichord is ruled, up to 1000 Hz, by various couplings between the normal modes of the soundboard and of the enclosed cavity. The necessary geometry for these to occur appears to be fairly explicit and so it would be interesting to know whether such a situation arose fortuitously (or indeed whether it just occurs in the authors' clavichord), for this most important area of the instrument's response is considerably enhanced by these events. Perhaps, rather than lucky, the early designers and builders of the clavichord possessed more insight than we suspect.

III. PERFORMANCE

In this section some measurements of a more subjective nature are presented with a view to describing the performance of the clavichord from a listener's and musician's point of view. All the following experiments were performed in an anechoic room where the ambient A-weighted sound level was about 30 dB. In the absence of a mechanical player the various measurements were made with several subjects of varying degrees of musical background striking the keys.

One feature of great interest in any instrument is the variation of intensity across the musical range. To measure this, four different experimenters in turn struck each note three times going from the bass to the treble and always endeavoring to strike the notes exactly evenly. In order to prevent them from compensating automatically for the perceived intensity in the manner of striking, the subjects wore earphones through which a masking white noise was played. The notes were recorded on tape through a pressure microphone one meter above the soundboard, and were subsequently analyzed by use of a measuring amplifier.

The results are plotted in Fig. 8(a). There is substantial agreement among the four players over that range of the instrument above the first octave. Evidently the "sponginess" of the keys in the lower register had disconcerted the players in their attempts to strike the keys evenly. Above C_4 there are four clearly defined peaks in the unweighted sound level with heights of up to 5 dB above the mean local level. It is immediately noticeable that these peaks fall at those notes whose fundamentals are enhanced by the admittance maxima of the plate, shown in Fig. 4. Since a substantial part of the energy in the radiated clavichord sound is in harmonics above the fundamental, at first sight this consistency would seem odd. However, it is the case here, fortuitously, that notes having second harmonics enhanced by the soundboard admittance peaks also lie within the same four peaks in Fig. 4. Thus the presence of these pronounced peaks is the chance result of the relative spacing of the plate resonances. The maximum in sound pressure level around E_5 has been broadened by the resonance of the portions of the strings between the bridge pins and the tuning pins. These strings all resonate within 30 Hz of 670 Hz, which is $\sim E_5$, so that when any note between D_5 and $F_5^{\#}$ is struck, these strings can all be heard to vibrate as well.

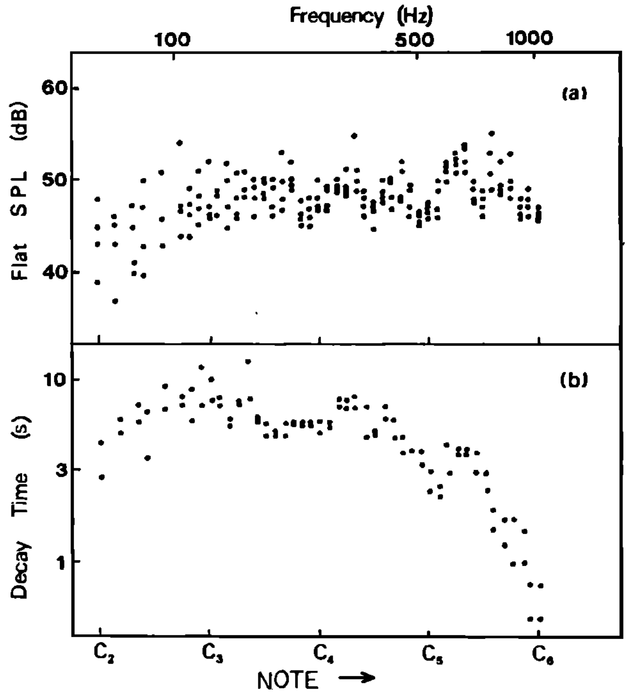

FIG. 8. (a) Measurements of the unweighted sound pressure level across the compass of the clavichord, obtained with separate subjects playing the notes. (b) The decay time to inaudibility of the notes across the clavichord compass, measured individually by two experimenters.

Apart from the maxima, the sound pressure level is even across the keyboard, like the harpsichord, for instance, which shows a nearly constant radiated sound pressure level throughout its range.[4] In the bass, however, despite the scattered nature of the data, there is a fairly obvious decline in the sound pressure level. Given the size of the soundboard this is not unexpected. The figure also clearly shows just how quiet the clavichord really is, the mean radiated sound pressure level at 1 m being only about 48 dB over most of the range and less in the far bass.

The decay time to inaudibility was measured by two experimenters using a stopwatch. Each one played the notes and took the average of three measurements for each note. The resultant data are plotted in Fig. 8(b) and, although the measurements were performed completely independently, the results are remarkably consistent.

The decay rate of sound depends on the rate of energy loss from the string, and it has already been shown that the main source of this loss is the energy transferred to the soundboard through the bridge. The measured data show that, although the decay time to inaudibility decreases towards the treble, this happens by no means smoothly. There is considerable scatter in the low notes, again reflecting their unsatisfactory "touch," and then an almost flat region covering most of the range, broken by a few small peaks. This is followed by a sharp decline in the treble. The maxima centered around E_4 and E_5 are again at strong soundboard resonances. Considering that the sound we are hearing after the first few tenths of a second is predominantly the "aftersound" as defined by Weinreich we would expect the decay rate to depend to a large extent on the relative size of the real and imaginary parts of the admittance at the bridge pin in question. Now, around these peaks the admittance is largely real and the bridge is mostly dissipative so that, provided the tuning is close to unison, one of the normal modes of the string pair is almost the purely antisymmetric one which allows minimal energy loss to the soundboard, thus causing the note to be sustained longer.

IV. CONCLUSION

The clavichord, as keyboard instruments go, looks deceptively simple at first sight, but on closer examination it has proven to have as many subtleties and complexities as any musical instrument. However, it is possible to understand in detail some aspects of its soundboard and string behavior and to correlate this understanding with various features of its performance. In fact, in several instances it provides an illustration of principles which are present but obscured in more complex musical instruments.

Some of the clavichord's more obvious faults seem to be the result of compromise for convenience in the instrument's design. It is a much easier instrument to build than a harpsichord, and cheaper, and it is a much easier instrument to possess since it is small and conveniently shaped. On the other hand, its development may have been arrested by the popularity of the harpsichord, so that solutions for some of the more obvious faults did not evolve. However, as with all musical instruments its irregularities have now become its distinguishing characteristics, and it is very pleasant when used with the music designed for it.

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[1]C. Sachs, *Real-Lexikon der Musikinstrumente* (Dover, New York, 1964), p. 216.

[2]A. H. Benade, *Fundamentals of Musical Acoustics* (Oxford U. P., New York, 1976), p. 354.

[3]G. Weinreich, "Coupled Piano Strings," J. Acoust. Soc. Am. 62, 1474–84 (1977).

[4]N. H. Fletcher, "Analysis of the Design and Performance of Harpshichords," Acustica 37, 139–47 (1977).

[5]S. Marcuse, *A Survey of Musical Instruments* (Harper and Row, New York, 1975), p. 245–256.

[6]J. C. Schelleng, "The violin as a circuit," J. Acoust. Soc. Am. 35, 326–38 (1963).

[7]I. M. Firth, "Physics of the guitar at the Helmholtz and first top plate resonances," J. Acoust. Soc. Am. 61, 588–593 (1977).

[8]G. Caldersmith, "Guitar as a reflex enclosure," J. Acoust. Soc. Am. 63, 1566–1575 (1978).