

AN APPARATUS FOR MEASURING STRING VIBRATION USING ELECTRIC FIELD SENSING

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ABSTRACT

Vibrating string measurements by electric field sensing make use of the phenomenon where the capacitance between a metal string and an electrode plate changes as a function of the distance between them. The measuring device introduced in this study is intended for measuring the vibrational movement of a conductive string in two polarizations and possibly in multiple points. The basic idea of the construction is to apply an alternating voltage of high enough frequency to the string, and to measure the capacitively coupled voltage from a small electrode plate nearby. This AC voltage is amplitude demodulated to obtain the displacement of the string as a function of time. The simple architecture of the measuring apparatus, its relatively small size, and minor effect to string vibration make it an interesting alternative to other string vibration measurement devices. Detailed construction of the apparatus will be described in the paper, as well as analysis on its properties. These include the accuracy of the method, signal-to-noise-ratio, and system design parameters that affect these properties. Interesting cases of string vibration (particularly of the guitar) will be analyzed and depicted.

1. INTRODUCTION

Methods for measuring a vibrating string's motion can roughly be divided into three categories; optical, electromagnetic, and electric field sensing methods. This paper introduces a device for measuring the vibration of a string in both polarizations using the latter technique. Generally, electric field sensing makes use of the phenomenon where the capacitance between two electrodes changes, when the distance between them is varied. Musical applications of electric field sensing are discussed in [1].

There are two basic techniques for performing string measurements with electric field sensing. The principle of the first method is similar to the function of condenser microphones. In this approach, a conducting string is grounded and DC voltage is applied to an electrode plate nearby. The string's movement modulates the voltage between the string and the plate, and information about the string's placement is obtained. The DC voltage applied to the plate must be sufficiently high, in order to allow the changing capacitance to be measured. This means that the coating of the sensing electrode must be designed with care, to avoid breaking the measuring equipment. A condenser microphone and preamplifier setup can be used as a measuring device, if the microphone's diaphragm is replaced with the grounded string, as is done in an earlier work [2]. If commercially available microphone preamps are used, the measurement of vibration in both polarization planes becomes difficult because the preamps are relatively large. An electrostatic

pickup for dual-polarization measurements of piano strings is presented by Weinreich [3].

The measuring device introduced in this paper is intended for measuring string vibration on a musical instrument using electric field sensing in a different way. The basic idea here is that an alternating voltage, the carrier signal, is applied to the string, and a small electrode is placed nearby. The voltage capacitively coupled to the electrode is then the carrier signal, amplitude-modulated by the movement of the string.

A voltage source follower is connected to the electrode plate to lower the output impedance of this measuring apparatus, and therefore to minimize the voltage drop in the cable to further analysis equipment. The signal is fed from the measuring apparatus to an AD-converter through an amplifier. The carrier signal is also fed to an AD-converter. Both signals are then read to a computer and the data concerning the distance between the string and the electrode is obtained by synchronous detection. Two electrodes are mounted on the measuring apparatus, thus allowing information of the string's placement to be obtained in both polarization planes, horizontal (i.e., parallel to the soundboard of a guitar) and vertical (i.e., perpendicular to the soundboard of a guitar).

2. THE APPARATUS

2.1. Construction of the apparatus

The measuring apparatus consists of two electrodes, an electric circuit containing two voltage source followers, and two 2-conductor microphone cables leading to the amplifier. The construction of the apparatus is illustrated in Figure 1. The circuit is enclosed by a brass casing, which is connected to the ground to make a Faraday cage, in order to cancel the effect of electromagnetic radiation to the circuit. The brass casing also provides mass to the apparatus, which together with a thin layer of polystyrene underneath the casing constitutes the apparatus less sensitive to external vibrations, e.g., the vibration of a soundboard in a musical instrument. The casing is sealed with two plastic plates and air duct tape.

The electrodes are made of two brass plates, dimensions being (15 × 10 × 0.6) mm, and are connected to the circuit with stiff copper wires of diameter 0.7 mm. The plates are placed at right angles relative to each other. The distance between the string and each electrode is chosen in these experiments to be approximately 5 mm when the string is at equilibrium, thus allowing vibrational amplitudes under 5 mm to occur on the string. A thin layer of insulating varnish is overlaid on the electrodes, in order to prevent galvanic coupling with the string.

The electric potential at a single point caused by an infinitely

long charged string (cylindrical charge) at distance r is of the form

$$V(r) = -\frac{1}{2\pi\epsilon_0} \lambda \ln \frac{r_{\text{string}}}{r} \quad (1)$$

where ϵ_0 is the permittivity constant of the vacuum, λ is the linear charge density of the string, and r_{string} is its radius. This implies that the voltage coupled to the electrode would depend on the logarithm of the distance between the electrode and string. However, if the amplitude of the string's vibrational movement is relatively small, the distance-voltage relationship can be approximated as linear, as is done in this study, or the nonlinearity can be compensated for in signal analysis.

The construction of the circuit is illustrated in Figure 2. The operating voltage for the circuit (6 V DC voltage) is produced with an external voltage source, and transferred to the circuit through cables. The cable used here is a shielded twisted pair, where the signal from the measuring apparatus and the operating voltage are in the inner conductors, while the shield is connected to the ground.

It must be noted that since the measuring device is relatively small, simple, and inexpensive, measurements at multiple points on the string can easily be conducted using several devices.

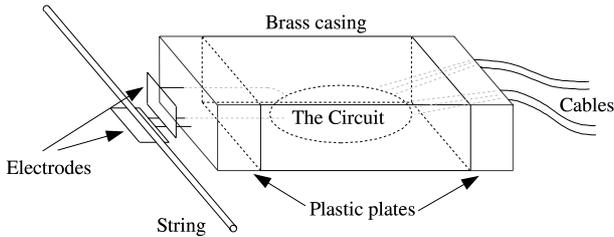


Figure 1: The measuring apparatus is designed for obtaining data from both vibration polarizations of a conductive string.

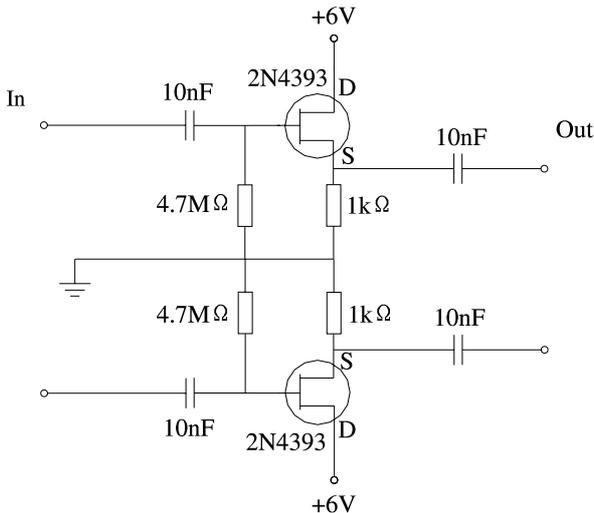


Figure 2: The circuit used in the measuring device is a two-channel voltage source follower. The main task of the circuit is to lower the output impedance of the apparatus, thus lowering the voltage drop in the cables to further measuring equipment.

2.2. Lowpass-filter-effect due to the longitudinal averaging of the electrode

It is important to note that because the measurements are carried out using electric fields and since the dimensions of the electrodes are not extremely small and they are not extremely close to the string, the longitudinal (in the direction of the string) spatial resolution is limited. The voltage capacitively coupled to the electrode is inversely proportional to a weighted average of its distance to a single point on the string. This phenomenon introduces a low-pass filter effect to the system, and it can be intuitively understood when considering the result of the averaging process. The wider the averaging window or higher the frequency of the displacement wave travelling in the string, the smaller displacement of mean voltage level from the equilibrium state is obtained. This low-pass effect would be reduced if the width of the electrodes could be made smaller, but this would also result in a lower signal level. Taking the electrode closer to the string would also help, but this would lead to increased nonlinearity due to Eq. 1.

3. CONSTRUCTION OF THE MEASUREMENT SETUP

The measurement setup consists of four main parts: a carrier signal source, a string vibration sensing device, an amplifier, and an analog-to-digital converter. The structure of the measurement setup is illustrated in Figure 3. The carrier signal used in the measurements is a steady 12 kHz sine-signal with peak-to-peak amplitude of 20 volts, produced with a signal generator. The signal generator also inserts some additive and multiplicative noise to the carrier signal, but this is not considered a serious problem since the amplitudes of the noise components are small, and the effect of noise is still reduced in the signal detection phase. Because the carrier signal has a relatively high signal level, it is fed to the AD-converter through a simple two-resistor voltage divider, denoted by R_1 and R_2 in Fig. 3.

The signal from the sensing apparatus is amplified with a low-noise mixer amplifier (denoted by B in Fig. 3), and then fed to an AD-converter. The sampling frequency used in the measurements is 48 kHz and the sample depth is 24 bits. It is possible to derive an expression for the voltage at the gate of the transistor using Figure 3. Clearly, the varying reactance of the string-electrode pair $X_{s,e}$ and the combined impedance $Z_{s\&i}$ of the stray capacitance and the source follower input resistor act as a voltage divider for the voltage V_0 generated in the signal generator, yielding for the gate voltage

$$V_{\text{gate}} = V_0 \frac{Z_{s\&i}}{X_{s,e} + Z_{s\&i}} + V_{\text{noise}} \quad (2)$$

and expressed in terms of the circuit components

$$V_{\text{gate}} = V_0 \frac{X_{\text{stray}} R_{\text{input}}}{X_{s,e} X_{\text{stray}} + X_{s,e} R_{\text{input}} + X_{\text{stray}} R_{\text{input}}} + V_{\text{noise}} \quad (3)$$

where V_{noise} is the voltage noise at the gate, discussed more thoroughly in subsection 3.2. X_{stray} and R_{input} denote the stray reactance between the ground and the gate and the input resistance of the source follower, respectively.

3.1. Signal detection

Since the carrier signal can be obtained easily from the signal generator, synchronous detection is used to obtain the data concerning the movement of the string. First, the carrier signal is phase shifted

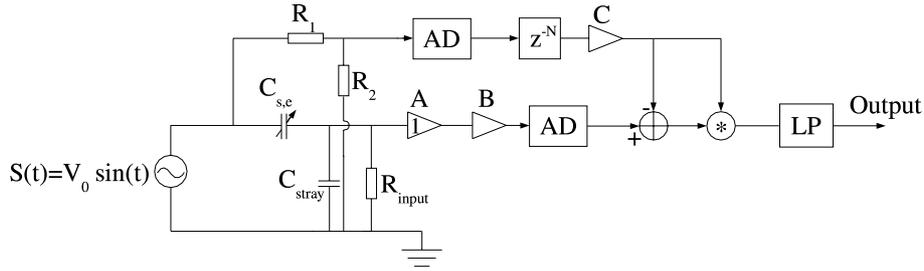


Figure 3: The measurement setup. The varying capacitance between the string and the electrode is denoted with $C_{s,e}$, while C_{stray} symbolizes the stray capacitance between the electrode and ground. R_{input} is the input resistance of the voltage follower circuit, presented in Figure 2. R_1 and R_2 present the resistance values of the voltage divider for lowering the carrier signal level. The signal generator is denoted with $S(t)$. Signal amplifiers A and B denote the voltage follower circuit and a mixer amplifier, while the amplifier block C is only a constant scaling coefficient used in the signal detection phase. The delay element z^{-N} is used in synchronizing the carrier signal with the signal from the apparatus. The output signal is lowpass-filtered by LP to remove the remaining carrier signal components.

in the time domain, so that it is in phase with the signal obtained from the measuring apparatus, and then normalized so that their amplitudes are approximately equal.

The carrier signal is then subtracted from the apparatus' output signal, and the resulting signal is multiplied with the phase- and amplitude-corrected carrier signal and finally lowpass-filtered at 10 kHz in order to remove the remaining high-frequency carrier. The final results can then be presented as the distance between the string and the electrode, as a function of time.

3.2. Theoretical study of SNR

The noise voltage at the gate of the transistor consists of three components: the input noise voltage of the transistor V_{nFET} , the noise voltage caused by the noise current of the transistor V_{iFET} and the noise voltage generated by the thermal noise of the input resistor V_{nI} ,

$$V_{noise} = V_{nFET} + V_{iFET} + V_{nI} \quad (4)$$

The equivalent input noise voltage of the JFET transistor is reported to be approximately $5 \text{ nV}/\sqrt{\text{Hz}}$ at frequency of 10 kHz. If the bandwidth of the signal is considered to be 10 kHz, the equivalent input noise of the JFET would then be 500 nV. Because the voltage output difference of the measuring apparatus between the distances of 5 mm to 6 mm is about 20 mV, and if the vibrational movement with amplitude 1 mm is considered as 0 dB, the equivalent input noise voltage of the transistor would cause a signal-to-noise ratio of about 92 dB.

The equivalent noise current of the transistor is specified as $0.4 \text{ fA}/\sqrt{\text{Hz}}$ at 10 kHz. A 10 kHz bandwidth would therefore result in a noise current of 40 fA, and this noise current combined with the $4.7 \text{ M}\Omega$ resistance of the input resistor would finally produce a noise voltage of $0.19 \text{ }\mu\text{V}$. Using the same SNR calculation method as above, we find that the noise current of the FET results in SNR of 100 dB, and so the effect of the noise current can therefore be neglected in practice.

The thermal noise of a resistor can be calculated from equation

$$V_{nR} = \sqrt{4kTB R} \quad (5)$$

where $k = 1.38 \cdot 10^{-23}$ (Boltzmann's constant), T is the absolute temperature of the resistor, B is the bandwidth of the signal, and R is the resistance. An input resistor of $4.7 \text{ M}\Omega$ would therefore result in a noise voltage of approximately $39.3 \text{ }\mu\text{V}_{\text{rms}}$.

The noise voltage V_{nI} at the gate of the FET due to the input resistance can be derived if the stray capacitance between the gate and the ground is known. The measurement data shows that the signal from the apparatus lags the signal obtained from the signal generator by approximately 30° . This suggests that the capacitive reactance of the stray capacitance at the carrier frequency is

$$X_{stray} = \frac{R}{\tan 30^\circ} \approx 8.14 \text{ M}\Omega, \quad (6)$$

and thus the noise voltage at the gate due to the input resistance can be presented as

$$V_{nI} = \frac{|jX_{stray}|}{|R + jX_{stray}|} V_{nR} \approx 34 \text{ }\mu\text{V}. \quad (7)$$

Assuming again that the string's movement with 1 mm amplitude would correspond to 0 dB, the thermal noise of the resistor would cause a signal-to-noise-ratio of approximately 55 dB. In real measurements however, lower SNR values were obtained. When comparing this noise level to the ones due to the transistor itself, it is obvious that the thermal noise produced in the input resistor is the main source of noise in this system, and it cannot be eliminated without dramatically changing the construction of the measuring apparatus.

If a higher carrier signal frequency would be used, the voltage noise at the gate could be made smaller, because the input resistor's contribution to the total impedance would be lower. On the other hand, if the carrier signal frequency would be very high, the signal detection would have to happen at hardware level instead of computational means after AD-conversion used here for simplicity. This would reduce the flexibility of the system and require more complex hardware. With approximative calculations we have found that the voltage noise produced in the transistor will be the dominating noise component for carrier frequencies higher than approximately 1.6 MHz.

4. MEASUREMENTS PERFORMED ON A GUITAR STRING

Signals obtained from a real measurement performed on a steel-string acoustic guitar are depicted in Figure 4. In this figure, signals from two different polarizations are plotted separately. Figure 5 shows data from the same measurement, illustrated so that different polarization movements correspond to different axes. It must be noted that in both figures the distance units not calibrated.

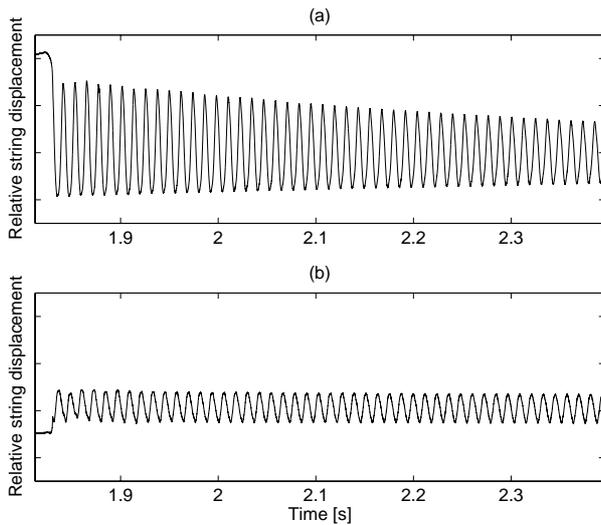


Figure 4: Measurement data from a plucked guitar string (E_2) obtained from the apparatus. The horizontal vibration component is depicted in (a), and the vertical component in (b). The string was plucked at its midpoint primarily in the horizontal direction, and the scaling in both (a) and (b) is the same. Note that the y-axis values in both figures are roughly in millimeters but not calibrated.

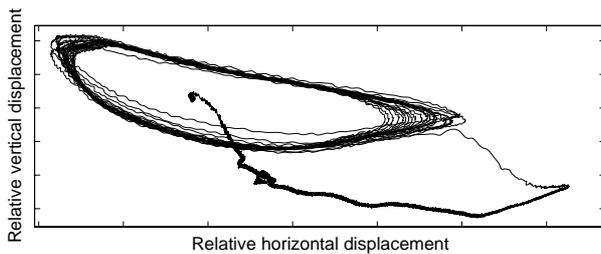


Figure 5: Data from a plucked guitar string. Horizontal movement of the string is presented in the x-axis, while vertical movement is presented in the y-axis. In this figure the pluck and approximately 0.2 seconds of vibrational movement is presented. The string was plucked primarily in the horizontal plane and same scaling was used for the x- and y-axes. The axis values were not calibrated.

5. DISCUSSION

There are many possible ways to improve the method proposed here to measure string vibration. Some of the possibilities are discussed in this section.

The dynamic range achieved in the prototype system, 40–50 dB, is useful for basic measurements of relatively large string displacements. The present dynamic range means 0 dB SNR for a displacement of about 3–10 μm . It could be however improved remarkably by several means. The most obvious one is to increase the frequency of the electric signal fed to the string. If the carrier frequency is above 1.6 MHz in the case described, the SNR could be up to 90 dB, which means that vibration displacements down to 0.03 μm will not be below measurement noise floor. At the same time the detection signal bandwidth can be increased since the low-pass filtering cutoff after demodulation can be made higher.

A signal processing technique improving SNR is to utilize the fact that after the attack the signal is concentrated around the

modal frequencies, while measurement noise is a wide-band signal. For example high-resolution autoregressive moving average (ARMA) modeling of a measured pluck response can be applied to the signal above noise floor and let the model predict the practically periodic signal down below the noise floor [4].

Another problem of the proposed measurement method is the inherent nonlinearity of the system as a function of string displacement. This can be compensated, however, by careful calibration of a correction curve, based on measurements.

The next problem, if real playing of the instrument is desired to be measured, is to isolate the player whose finger is touching the string not to change the electric field around the electrodes. This may be realized to some degree by shielding and connecting the player to ground potential.

The problem of spatial low-pass filtering, discussed in 2.2., is difficult to avoid since the capacitance between the string and the electrode is spatially distributed. Again, to some degree it can be compensated by inverse filtering of the low-pass effect caused by spatial averaging. Another possibility is, if there are many electrodes along the string, to do spatial filtering with the channel outputs in order to counteract the effect.

6. CONCLUSIONS

We have presented a principle for measuring string vibrations in two polarizations and in multiple points along a metal string using electric field sensing. A prototype device was constructed that senses capacitively the distance of string from a small electrode using AC voltage carrier fed to the string. The signal from a sensing electrode is down-modulated and low-pass filtered to obtain an audio signal proportional to string displacement.

Theoretical SNR of the device was also derived, and two-polarization data from a real measurement on a steel-string guitar was presented. Although the prototype system has limitations in performance and functionality, such as relatively small dynamic range, the method shows potential to be improved further by proper combination of dedicated hardware and software.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

- [1] J. Paradiso and N. Gershenfeld, "Musical Applications of Electric Field Sensing," *Computer Music Journal*, vol. 21, no. 2, 1997.
- [2] X. Boutillon, "Model for piano hammers: Experimental determination and digital simulation," *Journal of the Acoustical Society of America*, vol. 83, pp. 746, 1988.
- [3] G. Weinreich, "Coupled Piano Strings," *Journal of the Acoustical Society of America*, vol. 62, no. 6, pp. 1474–1484, 1977.
- [4] M. Karjalainen, P. Esquef, P. Antsalo, A. Mäkivirta, and V. Välimäki, "Frequency-zooming arma modeling of resonant and reverberant systems," *Journal of the Audio Engineering Society*, vol. 50, no. 12, pp. 1012, 2002.