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CAPACITIVE AXIAL POSITION AND SPEED TRANSDUCTION SYSTEM

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ABSTRACT

A new and inexpensive circuit arrangement of a capacitive axial position and speed transduction system is described. Design details and the theory of operation of the device are briefly outlined together with performance results.

RESUMEN

Se describe un circuito económico y novedoso para un sistema transductor capacitivo que mide posición y velocidad de movimientos axia les. Los detalles de diseño y la teoría de operación del dispositivo se describen brevemente, así como los resultados de funcionamiento.

1. INTRODUCTION

An accurate measurement of axial position and speed of moving bodies is required in many instrumentation and control applications. For the measurement of these quantities there are various methods than can be employed. Among them we can mention optical interferometric techniques[1-3], the use of linear variable differential transformers[4-6], the method based on the detection of Foucault currents produced in some mobile metallic part of the body whose position or speed is being measured[7], or the use of differential variable-gap capacitive transducers[8,9]. With the exception of the latter devices most of the mentioned methods are generally complex, require quite elaborate designs or tend to be expensive.

The purpose of this paper is to describe a new and inexpensive circuit arrangement of a differential variable gap capacitive transducer. It will be shown that the new circuit arrangement has advantages over the conventional system using the same transducer[8,9].

Design details and the theory of operation of this new arrangement will be outlined here together with performance results that show the sensitivity characteristics of the device.

2. DESCRIPTION OF THE DEVICE

The complete transduction system consists of a capacitive transducer, a demodulator, an oscillator and a differentiating circuit. The capacitive transducer shown in Fig. 1 is basically a three terminal capacitor consisting of three parallel metal discs; two of the discs are fixed while the third, located between them, is movable. This disc is attached to an axial shaft that is fastened to the body whose position or characteristics of motion are the object of study.

In the instrument proposed, a fixed frequency oscillator applies a sine-wave voltage to the two fixed parallel plates of the capacitive transducer. In this way the output in the movable plate is the applied oscillator signal modulated by the form of the axial displacement of the inner movable capacitor terminal.

The information about the displacement of the movable plate is recovered by demodulation of the signal taken from the movable terminal. As we shall show, this signal is proportional to the displacement of the movable plate. The speed is simply obtained by differentiating this signal.

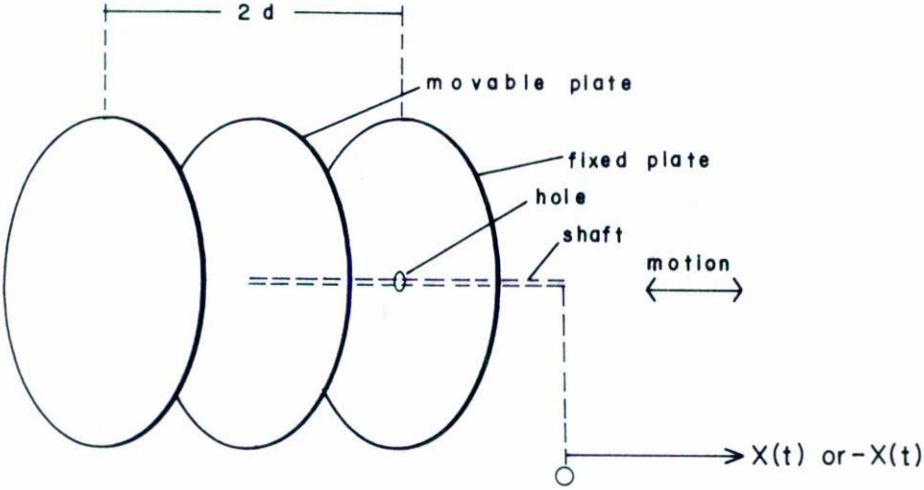

Fig. 1 Sketch of the capacitive transducer. Separation between fixed plates = 2d. Displacement from midway position = -X(t) or +X(t).

3. THEORY OF OPERATION

Figure 2 illustrates the scheme adopted to obtain an output voltage $e_0(t)$ proportional to the displacement of the movable terminal.

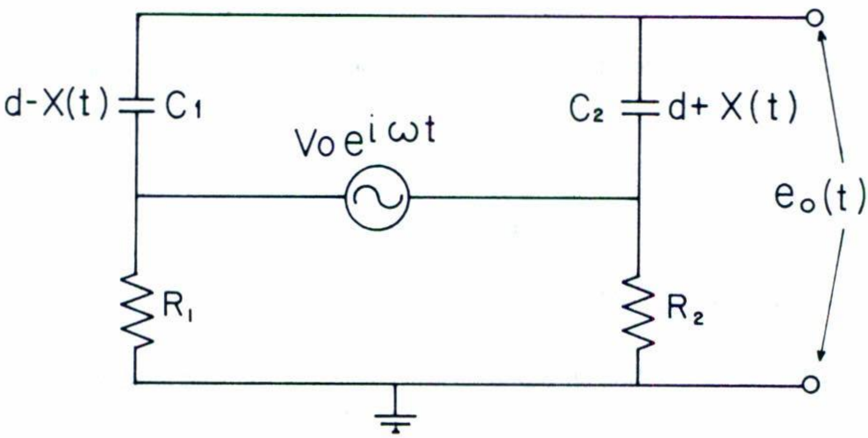

Fig. 2 Scheme adopted to obtain an output voltave $e_0(t)$ from the capacitive transducer.

Let d be the separation between the movable plate and any of the fixed plates when the former is positioned midway between the latter ones, and let X(t) be the displacement of the movable plate from its mid way position. Then the values of the capacitances of the two capacitors formed by the movable and each fixed plate are

$$C_1(t) = \frac{C_0}{1 - \frac{X(t)}{d}} \quad \text{and} \quad C_2(t) = \frac{C_0}{1 + \frac{X(t)}{d}} \quad ,$$

where C_0 is the capacitance of either $C_1(t)$ or $C_2(t)$ when $X(t) = 0$.

A simple analysis in terms of the electric charge, of the circuit shown in Fig. 2, yields

$$R \frac{dq}{dt} + \frac{q}{C_0} = V_0 e^{-i\omega t} \quad , \tag{1}$$

where $R = R_1 = R_2$, and V_0 and ω are the amplitude and frequency of the oscillator's signal.

Solving Eq. (1), it is found after rationalizing that the real part of the output voltage $e_0(t)$ is given by

$$\text{Re } e_0(t) = V_0 \frac{X(t)}{d} \frac{\cos \omega t + \omega\tau \sin \omega t - e^{-t/\tau}}{1 + \omega^2 \tau^2} \quad , \tag{2}$$

where $\tau = R\, C_0/2$.

It must be noticed that it is always possible to choose ω and τ in such a way that

$$\omega \tau << 1 \quad , \tag{3}$$

in which case Eq. (2) becomes approximately

$$\text{Re } e_0(t) = V_0 \frac{X(t)}{d} \cos \omega t \quad .$$

By demodulation of this output a signal proportional to the displacement X(t) is obtained:

$$\text{Dem}\ (\text{Re}\ e_0(t)) = \frac{V_0}{d} X(t) \quad . \tag{4}$$

This signal in turn can be electronically differentiated to yield $\dot{X}(t)$, the instantaneous speed.

In order to ease the observation of the modulation that the motion of the sample body produces in the carrier signal, the oscillator's frequency ω should be much greater than the frequency of motion of the sample. This, together with Eq. (3), are the design criteria to follow when choosing ω.

Figure 3 shows a conventional differential variable gap capacitive transducer system. This uses the same capacitor but has opposite phases connected to their outer plates. An analysis in terms of the electric charge of this circuit yields the same expression mentioned in Eq. (1). This means that, in principle, the performance of both, the transducer presented in this work and the conventional system must be identical. However, the new arrangement employs two oscillators connected in series (for example, a center tapped transformer), allowing a differential mode operation which has the great advantage of shielding the system from external noise.

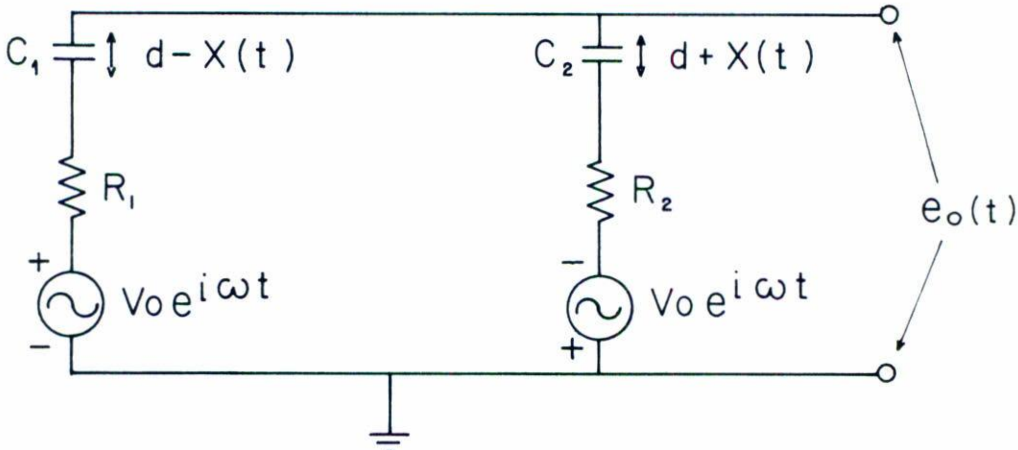

Fig. 3 Conventional scheme (see Refs. 8 and 9).

4. DETAILS OF CONSTRUCTION

As the starting point of the design a speed range from 0.0 to 0.1 ms^{-1} and maximum displacement of 10^{-3} m were chosen as the motion characteristics of the sample under observation. The reason being that these conditions can be easily simulated by fastening the transducer to a coaxial loudspeaker. This array has the additional advantage that the transducer response can be tested by driving the loudspeaker with several different waveforms. In this way, the device's principle of operation can be easily tested.

To study the system response under the above-mentioned ranges, a lightweight capacitive transducer had to be fabricated in order to avoid significant mechanical loading to the loudspeaker. For this purpose, the three plates of the capacitive transducer were made of a thin copper sheet (0.18 mm), thin enough to keep a light weight design but rigid enough to avoid spurious mechanical vibrations.

Figure 4 shows a sectional view of the capacitor. The movable part of the transducer consists of the capacitor's inner disc and of a brass shaft soldered to this disc. Special attention must be given to achieve a proper alignment of the shaft and the hole through the external capacitor's housing in order to avoid contact. The design of the electronic circuits is conventional; however, since the three plate transducer posseses a high impedance, some noise and interference problems may arise in the circuit, consequently, a matching circuit must follow the transducer's output. This is shown in Fig. 5, together with the demodulator and differentiating circuits. The frequency of the oscillator shown in Fig. 5 was of 50 KHz in accordance to the criteria mentioned in the previous section.

Finally, it must be mentioned that the design of the transduction system has not been optimized; nevertheless, it provides a simple way of testing the principle of operation.

5. PERFORMANCE

Tests were performed using frequencies in the range of 10 to

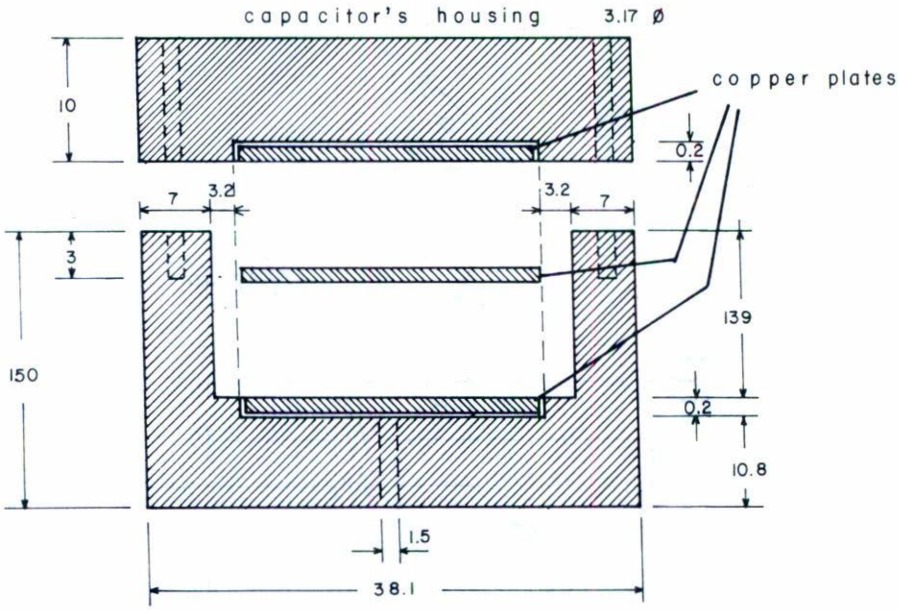

Fig. 4 Cross section of the transducer, all dimensions in mm. (Not to scale).

200 Hz for the several different waveforms used to drive the coaxial loudspeaker. Figure 6 shows the different responses through the circuit when applying a sawtooth signal. The CRO signals displayed in this figure show a good linear response of the device within the tested range.

The sensitivity "S" of the transducer can be defined as the output voltage per milimeter of displacement. In the present test "S" was of the order of 150 mV/mm. Sensitivities of the order of 2 mV are simple to achieve in a CRO, therefore a displacement resolution of 13.3 μm can be obtained with the device. The sensitivity for the speed output is in the range of 1.6 mV/mm/sec. thus speeds as low as 0.125 mm/sec. can be observed.

Possible phase-shifts in the demodulation transformer which

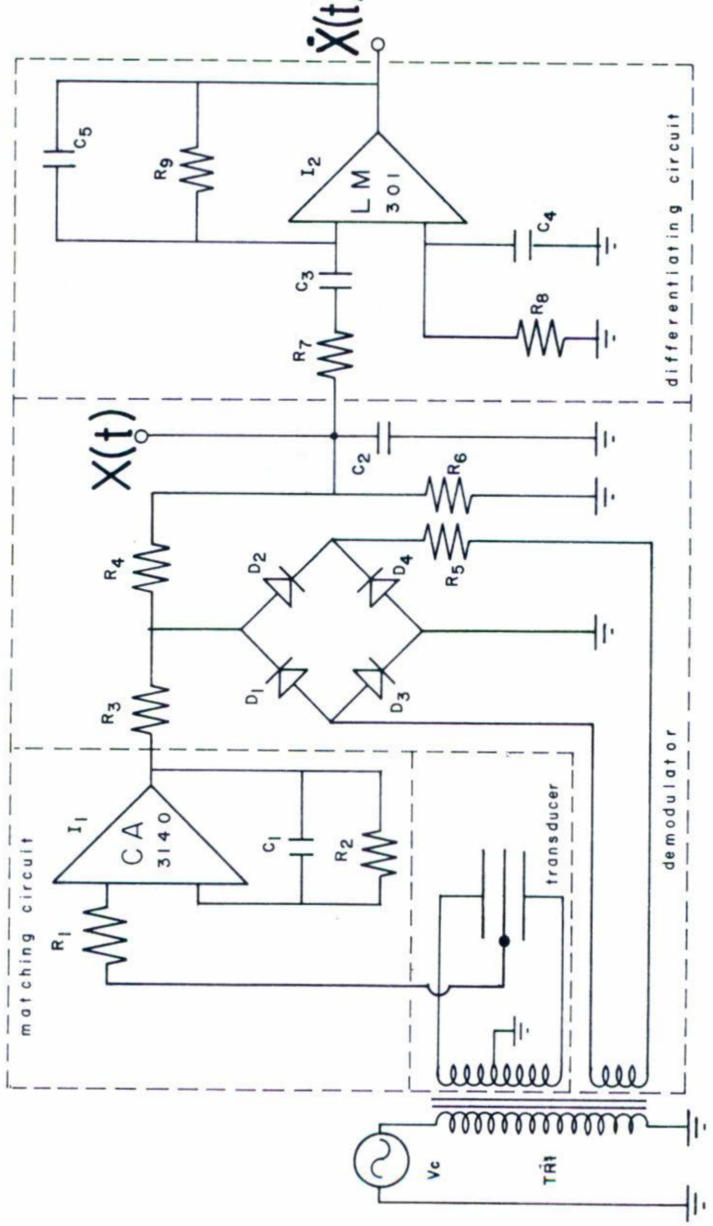

Fig. 5 Circuit diagram of the transduction system.

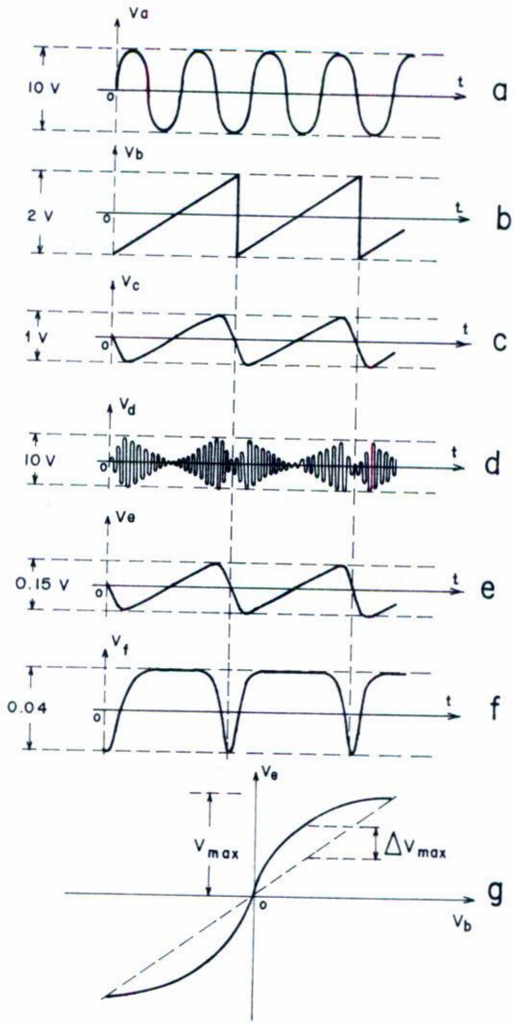

Fig. 6 Schematical representation of typical waveforms, responses and linearity in the experimental array. Representations not to scale.

a) Oscillator waveforms (50 KHz). b) Sawtooth signal applied to an audio amplifier used to drive the loudspeaker (10 - 200 Hz). c) Loudspeaker driving signal (10 - 200 Hz). d) Transducer output. e) Detected output waveform (displacement). f) Differentiating circuit output (speed). g) X - Y CRO display showing the linearity of the experimental array. Signal c) is applied to the X-axis CRO deflection plates, while e) is applied to the X-axis CRO deflection plates.

Non linearity "L" = $100 \left|\Delta V\right|_{(max)} / V_{(max)}$. "L" less than 5%.

will contribute to a DC offset to the X(t) output were not detected.

The transducer can be calibrated with the aid of another speed detection device. In the present case a Wissel MVC-450 Mössbauer velocity calibrator based on laser interferometry was used for calibrating and checking accurately the operation of the transducer.

Finally, it must be mentioned that the performance of the conventional system was also observed, resulting in a noticeable high noise level output due to the common mode operation of this conventional arrangement.

6. CONCLUSIONS

The device has shown good sensitivity and a reasonable linear behaviour, it is inexpensive, simple and extremely versatile. It offers the additional advantage of having low noise characteristics when compared to the conventional system.

APPENDIX

List of parts of the circuit shown in Fig. 5.

Resistors

R_1	- Carbon	film	10	KΩ	1/2 W
R_2	"	"	2.2	KΩ	"
R_3	"	"	3.9	KΩ	"
R_4	"	"	33	KΩ	"
R_5	"	"	560	KΩ	"
R_6, R_8	"	"	180	KΩ	"
R_7	"	"	150	Ω	"
R_9	"	"	150	KΩ	"

Capacitors

C_1, C_2	polyester	0.68μf
C_3	"	1μf
C_4	"	0.47μf
C_5	ceramic	720pf

Integrated Circuits

I_1 Operational Amplifier CA 3140 RCA

I_2 Operational Amplifier LM 301 National

Transformer

TR1 Ferrite Core 1:1 CT

Diodes

D_1-D_2 Signal Diode 1N914

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