function and to provide a feedforward compensation for power supply amplitude perturbations. A general formula to calculate the amplitude and waveform of the dither has been deduced. A phase control application to a separately excited dc motor has been also presented.

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A High Sensitivity Measuring Technique for Capacitive Sensor Transducers

MAURO BRAMANTI

I. INTRODUCTION

The transducing of several different physical variables (forces, pressures, displacements, liquid, solid, or gaseous material flows and so on) into electrical quantities is a very common problem in both control and industrial electronics and in biomedical instrumentation engineering.

Of the large variety of sensors and transducers that have been proposed to meet the different requirements of these fields, capacitive transducers are the most frequently encountered. However, the use of these types of transducers always implies the choice of a suitable capacitance measuring technique with good sensitivity and reliability.

Although numerous measuring methods have already been proposed, there is still interest in new solutions and techniques [1]-[3]. From a general point of view, these techniques can be classified in the following basic types: bridge-type measuring techniques, where sensor capacity variations cause unbalance of ac bridge circuits, frequency domain measuring techniques, where the sensor capacity controls the frequency of an oscillating system, and time-domain measuring techniques, where variations of sensor capacity modify the temporal length of a suitably generated electrical signal.

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The author is with IEI-CNR, Pisa, Italy.
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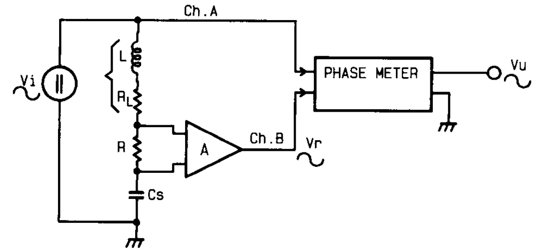

Fig. 1. Logical diagram of the proposed capacitance measuring technique.

A performance comparison of the above measuring methods is neither simple nor is it the purpose of this letter. Nevertheless, it can be asserted that none of the methods proposed so far are completely satisfactory when measuring very low capacity changes (e.g., less than 1 pF). Therefore, the development of techniques for detecting capacity variations in this range remains an interesting problem.

In this letter, a particular measuring technique is proposed for a capacitive-type sensor that has been developed to measure the density of dielectric powder gaseous suspensions.

However, the technique can be usefully applied in many other cases where capacitive sensors are present.

II. THE PROPOSED TECHNIQUE

The basic principle of the technique proposed here is to measure the variations dC_S of sensor capacitance C_S by measuring the phase shift $d\psi$ between voltage and current in a series RLC circuit tuned to resonance.

This is shown in Fig. 1 where

- V_i sinusoidal voltage signal of frequency $f = \omega/2\pi$
- C_s capacitance of the sensor
- L, R_L inductance, with its loss resistance, used for tuning capacitance C_s at frequency f
- R very low value pick-up resistor used to measure the current in the circuit
- A balanced input amplifier

The phase ψ between V_i and V_r is

$$\psi = -tg^{-1}\frac{\omega L - 1/\omega C_s}{R + R_L}. \quad (1)$$

For a change dC_s is the sensor capacity

$$d\psi = -\frac{1}{1 + \frac{(\omega L - 1/\omega C_s)^2}{(R + R_L)^2}} \cdot \frac{1}{\omega(R + R_L)}\frac{1}{C_s^2}dC_s. \quad (2)$$

At resonance, i.e., for $\omega = \omega_0 = 1/\sqrt{LC_s}$, (2) yields

$$d\psi = -\frac{1}{\omega(R + R_L)C_s^2}dC_s. \quad (3)$$

The quality factor of the resonant circuit is defined as

$$Q = \frac{1}{\omega C_s(R_L + R)} \quad (4)$$

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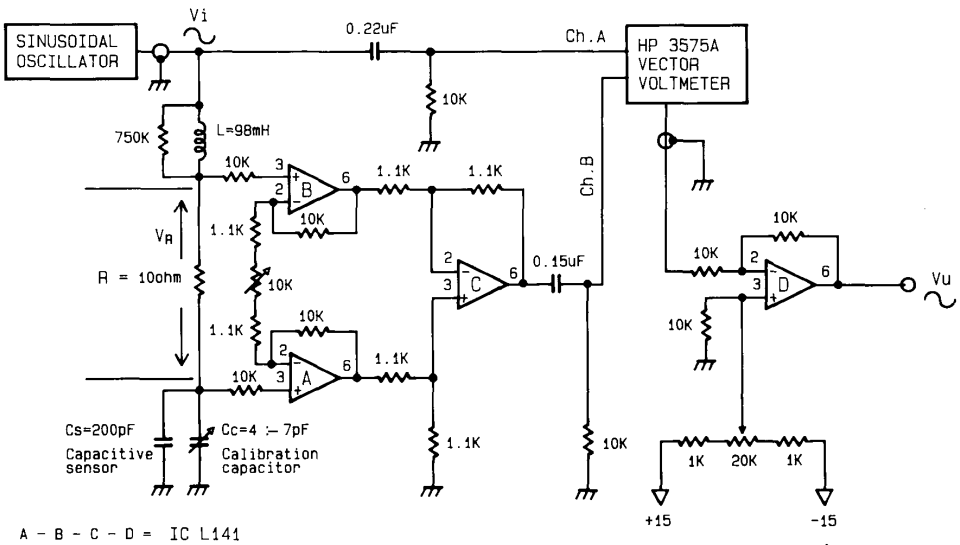

Fig. 2. Electrical diagram of the proposed capacitance measuring technique.

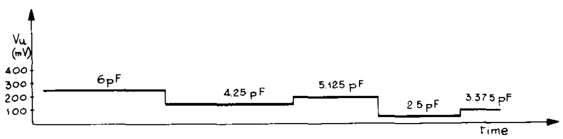

Fig. 3. Calibration diagram of the whole measuring system.

so that (3) may be written as

$$d\psi = -Q\frac{dC_s}{C_s}. \qquad (5)$$

Equation (5) gives the relation between the measured variable ψ and the relative variation of the sensor capacitance. It shows that the sensitivity of the technique is only limited by the quality factor of the resonant circuit.

To estimate the sensitivity of this method, let us assume $Q \cong 100$ and the availability of a commercial phase meter with a measuring performance of 10 mV/(°); from (5), it then results that

$$\frac{dC_s}{C_s} \cong 10^{-4} \qquad (6)$$

The assumption $Q = 100$ is not a severe condition and can be fulfilled for a very wide range of the chosen working frequency f. It should also be noted that from (4), we have

$$\frac{dQ}{Q} = -\frac{dC_s}{C_s} \qquad (7)$$

so that the value Q can be assumed constant during the measuring of dC_s.

III. Experimental Results and Applications

The technique proposed above was tested by implementing the circuit shown in Fig. 2; the measuring frequency f was 36 kHz. Phase ψ was measured by the vector voltmeter HP3575A, which has a measuring sensitivity of 10 mV/(°).

The mean value of the capacitive sensor C_s was 200 pF so that an inductance $L = 98$ mH was required to fulfill the resonance condition; an R value of 100 Ω was used. To eliminate instability phenomena encountered in the amplification of signal V_R, a loading resistor for L was introduced; a final value for Q of about 20 resulted.

The adjustable gain introduced in the amplifier of the prototype shown in Fig. 2 may be eliminated in a final version of the instrument; the high pass filters at the input of channels A and B were introduced only to avoid damage to the HP 3575A from eventual dc values at the output of the sinusoidal oscillator and amplifier.

The offset adjust circuit present in the output operational amplifier was introduced to compensate the dc level at the phase output of the vector voltmeter.

The capacitor C_c allowed a calibration of the whole measuring system. Fig. 3 reports the diagram obtained recording the V_u versus time for different values of C_c. It resulted in a good linear relation between V_u and the variations of C_c values without any retuning of the circuits; despite the reduced value of Q, the final sensitivity was about 60 mV/pF. It is interesting to note that the system is capable of continuously monitoring variations of dC_s.

The system shown in Fig. 2 was successfully used, for example, to determine the density of different material powder suspensions in air by measuring the relative dielectric constant ϵ_r of the suspension itself. The sensor used was a coaxial cylindrical capacitor with outer and inner diameters $\Phi_2 = 96$ mm, $\Phi_1 = 60$ mm, respectively, and a length $1 = 1700$ mm. The variation dC_s with respect to the C_s value (relative to the free air condition) was measured on the basis of the calibration diagram relating C_s to V_u (again, see Fig. 3).

In this case, we have

$$\frac{dC_s}{C_s} = d\epsilon_r \qquad (7)$$

so that the measured sensitivity is about 10 mV for $d\epsilon_r \cong 1/1000$.

Finally, the relation between $d\epsilon_r$ and the density of suspension was assumed to be expressed by the equation [4]

$$d\epsilon_r = \frac{q}{G}(\epsilon_{rm} - 1) \qquad (8)$$

where q is the density of the suspension, ϵ_{rm} is the relative dielectric permittivity, and G is the density of particulate material.

In the experiments in our laboratories, we encountered no problems arising from temperature effects or the resonant frequency drift.

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