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Electrocapillary elements. V. Acceleration meters working in short-circuit output conditions

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The idea of a system for measuring the acceleration of an alternating movement is presented. The system comprises an electrocapillary transducer and an electronic system consisting of a current–voltage converter and an integrating system. The transducer output is in a short-circuit state because it is connected to the current–voltage converter. The system presented can also be applied to construction of an alternating pressure amplitude meter.

1. Introduction

Among the fundamental applications of electrocapillary elements are gauges for measuring the acceleration amplitude of vibrational movement [1–4]. Electrocapillary transducers may be used for this in the frequency range below the resonance value at which their mechanical properties are determined by inner stiffness [3]. In previously developed acceleration meters working in open-circuit conditions, the input impedance of the measuring device is high compared with the output impedance of the transducer. The electrical equivalent circuit of acceleration meters resulting from the general equivalent circuit of electrocapillary elements [5, 6] comprises an alternating voltage source which simulates the alternating force which acts on the mass of the transducer filling, an electrochemical capacitance at the mercury–electrolyte solution interface and a mechanical capacitance which simulates the transducer stiffness [7].

Over the frequency range at which the electrocapillary transducers may be used as acceleration meters their characteristics are flat, i.e. frequency independent. The useful range of an acceleration meter has a high-frequency limit determined by the mechanical resonance effect [5] which occurs at about 0.6 of the resonance frequency value [3]. The low-frequency limit of the acceleration meter working with an open-output is determined by the Warburg impedance related to the presence of mercury ions in the transducer solution. A detailed discussion presented by Figaszewski *et al.* [8] has demonstrated that a low mercury ion concentration is required to decrease the low-frequency limit of the acceleration meter range. However, a certain quantity of mercury ions in the solution is necessary in order to insure the presence of a stable electric charge at the mercury–electrolyte solution interface. Thus, the low-frequency limit of the acceleration meter range results from the very nature of electrocapillary transducer action.

Figaszewski *et al.* [8] demonstrated that a mercurous ion concentration less than 1.1×10^{-7} mol dm^{-3} is required to attain an increase in Warburg impedance such that a flat characteristic is obtained from 1 Hz onwards with a 5% accuracy. A solution of composition 1.1 mol dm^{-3} Na_2SO_4 + 0.1 mol dm^{-3} H_2SO_4 proposed by the authors as optimum contained about 1 mol dm^{-3} free sulphate ions thereby assuring a mercurous ion concentration below 6.2×10^{-7} mol dm^{-3} (the solubility product $[Hg_2^{2+}][SO_4^{2-}] = 6.2 \times 10^{-7}$ mol^2 dm^{-6}).

A calculation similar to that presented by Figaszewski *et al.* [8] demonstrates that the Warburg impedance attains a value which insures a flat acceleration meter characteristic from 20 Hz onwards at that concentration. In practice, this range is more advantageous because of the reaction resistance and the adsorption capacitance present in the Faradaic branch of the equivalent circuit of

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electrochemical impedance and because of the approximate character of the relationship (Equation 5) given by Figaszewski *et al.* [8]. Anyway, a low-frequency limit of the acceleration meter range caused by the presence of mercurous ions in solution is unavoidable due to the operation principle of electrocapillary transducers working under open-circuit conditions.

Another application of the electrocapillary transducer is the sensing device for the measurement of alternating pressure amplitude [9]. The idea of alternating pressure manometers is based on the same premises as those of acceleration meters, but the alternating mechanical force stimulating the movement of the capillary filling is applied in different ways in the two cases. In the case of acceleration meters the force originates from vibrations of the casing and is transmitted to the mass of the electrolyte, whereas in the case of manometers it is due to an alternating gas pressure which makes contact with the electrolyte directly [9]. The properties of acceleration meters and manometers are described in terms of the same electrical equivalent circuit [7]. Thus, both the acceleration meters and the electrocapillary manometers working under open-circuit conditions are characterized by the same inconvenience of having a low-frequency limit of the flat characteristic range.

It is the aim of this paper to present a design for an electrocapillary transducer in which the acceleration meter range has a low-frequency limit determined by the outer measuring system only. The idea may also be applied to the measurement of alternating pressure by means of electrocapillary transducers.

2. The concept of acceleration meters working under short-circuit output conditions

The electrical equivalent circuit of electrocapillary transducers described by Figaszewski and Koczorowski [5] undergoes a marked simplification under particular measurement conditions. Some elements of the circuit modelling the phenomena occurring in the transducer are no longer necessary and the effects of their properties on the behaviour of the transducer are eliminated. In conditions where the electrical impedance of the interfaces is in a short-circuit state, i.e. where the load resistance, R, is negligible compared to the inner impedance of the transducer, then

$$R \ll Z_{in} \quad (1)$$

and the resistance of the solution, R_0, is negligible compared to the electrochemical impedance, Z_{el},

$$R_0 \ll Z_{el}. \quad (2)$$

Over a frequency range where the resonance frequency, f_0, has no influence,

$$f \ll f_0, \quad (3)$$

and the properties of the transducer are determined by its mechanical parameters: the mass of filling, m, and the stiffness coefficient, k, as well as by the coefficient characterizing the mechanical–electrical energy transduction, α, also called the electrocapillary coefficient. Under such conditions the electrical equivalent circuit of the transducer undergoes a simplification and comprises only a source of alternating voltage, E, simulating the mechanical force acting on the mass of the filling, and a mechanical capacitance, C_m, simulating the inner stiffness of the transducer

$$E = m\alpha\ddot{x} \quad (4)$$

$$C_m^{-1} = k\alpha^2 \quad (5)$$

where $\ddot{x}$ denotes the acceleration amplitude of the transducer capillary. The coefficient, α, is determined by the capillary diameter, ϕ, and by the charge density, q, at the mercury–solution interface

$$\alpha = \frac{1}{\pi\phi q}. \quad (6)$$

If the conditions of Equations 1 to 3 are fulfilled, the output short-circuit current, I_{sh}, is described by the relationship

$$I_{sh} = E\omega C_m \quad (7)$$

where ω is the frequency. In the above working conditions, the electrocapillary transducer may be applied to measurements of the vibrational movement acceleration amplitude. To this aim the output short-circuit current is converted into voltage and integrated before being fed into a voltmeter. The circuit accomplishing these functions is presented in Fig. 1. Here the electrocapillary transducer is represented by an alternating electromotive force, E, and by a mechanical capacitance,

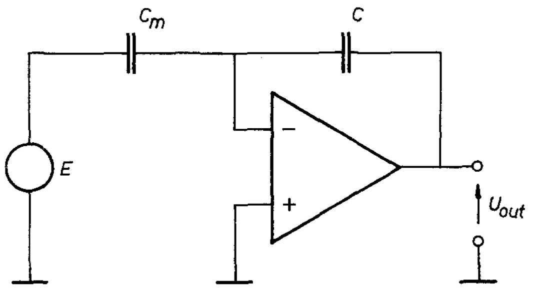

Fig. 1. Electrocapillary acceleration meter comprising a current–voltage converter and an integrating system.

C_m. The transducer output is connected directly to the output of an inverting operational amplifier [10] which works in a current–voltage converter system and in an integrating system simultaneously. As the input resistance of the current–voltage converter is negligible the transducer output works practically in short-circuit conditions. The so-called apparent short-circuit is accomplished by an operational amplifier which maintains the inverting input potential equal to the ground potential.

The output voltage amplitude, U_{out}, of the circuit presented in Fig. 1 is described by the relationship:

$$U_{out} = E \frac{C_m}{C} \quad (8)$$

where C denotes the capacitance in the feedback of the operational amplifier. U_{out} and E denote alternating voltage amplitudes. The sign inversion occurring in the inverting amplifier system [10] has been neglected in Equation 8. Equations 4, 5, 6 and 8 yield the dependence of the output voltage on the acceleration amplitude and on the construction parameters of the transducer:

$$U_{out} = \frac{\phi m q \ddot{x}}{kC} \quad (9)$$

The application of electrocapillary transducers with a short-circuit output to acceleration amplitude measurements is based on this expression.

The above design for electrocapillary acceleration meters where the transducer works in short-circuit output conditions does not involve any factors which would impose a low-frequency limit. Equations 4–7 resulting from the electrical equivalent circuit are correct even at infinitely low frequencies. The electrical equivalent circuit was checked experimentally for frequencies from 3×10^{-3} Hz by Koczorowski *et al.* [9]. Equation 2 is fulfilled more rigorously at lower frequencies because of the increase in impedance, Z_{el}. The frequency range where the electrocapillary transducer in the proposed system can be applied to the measurements of acceleration amplitude has a low-frequency limit resulting only from the quality of the electronic components. Operational amplifiers, characterized by very low polarizing current and offset current values available at present, e.g. 740, 108 or 777 μA, make it possible to accomplish a current–voltage signal conversion and integration even at very low frequencies.

3. Experimental procedure

The preparation of materials and electrocapillary transducers have been described elsewhere [3, 5, 6]. The vibrometric apparatus for measuring the frequency input characteristics of the transducers have also been described elsewhere [3, 5]. The amplifier, comprising the current–voltage converter, and accomplishing the integration (Fig. 1) was based on the Type 777 μA operational amplifier. The circuit contained an offset current compensator and a polarizing current compensator. A 1 *nF* capacitor was placed in the feedback system of the operational amplifier. A resistance voltage divider was connected in parallel to the capacitor in order to protect the capacitor against charging by any noncompensated polarizing current or offset current. The current divider was equivalent to a 10^9 Ω resistor.

The limiting frequency above which the system accomplished the integrator function was

$$f_{lim} = \frac{1}{2\pi RC} \approx 0.15 \text{ Hz.} \quad (10)$$

A lowering of the limiting frequency requires that either a higher capacitance be used, which would lower the output voltage of the system according to Equation 9, or a higher resistance R be introduced. A higher resistance R connected in the feedback of the operational amplifier parallel to the capacitor requires a sufficiently low constant current (both the offset and the polarizing one), such that its flow through the resistance R causes a constant component to appear at the output of the system.

Table 1. Construction parameters of electrocapillary transducers

Transducer number	*n*	*m* (mg)	$_1l_p$ (mm)	$_2l_p$ (mm)
12	10	127	0.15	0.15
13	20	139	0	0

4. Results and discussion

The concept of electrocapillary acceleration meters working under short-circuit output conditions was checked by measuring the frequency and amplitude characteristics of a series of transducers. The transducers were filled with aqueous 3.7 mol dm^{-3} sulphuric acid solutions which had high specific conductance, thereby fulfilling Equation 2. Transducers were prepared in capillaries of 0.44 mm diameter. Other structural parameters of the filling were: the number of interfaces, n, the mass of the filling, m, and the lengths of the air columns at the transducer ends, $_1l_p$ and $_2l_p$, which are given in Table 1.

Typical frequency characteristics of the acceleration meters are presented in Fig. 2 for the acceleration amplitude $\ddot{x} = 5$ m s^{-2}. The acceleration meter ranges of transducer nos 12 and 13 were 100 and 200 Hz, respectively. The amplitude characteristics of these transducers are presented in Fig. 3 in the acceleration meter range.

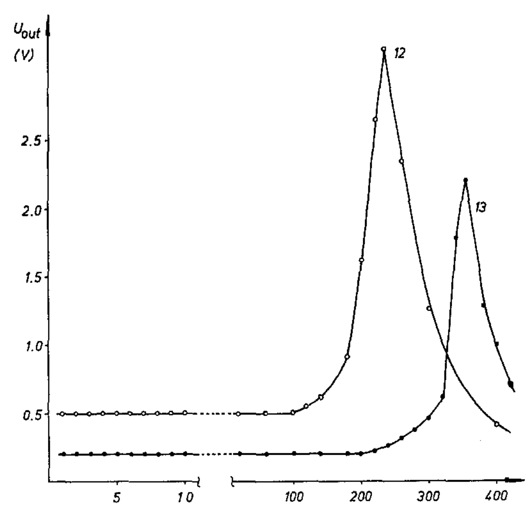

Fig. 2. Frequency characteristics of electrocapillary acceleration meters.

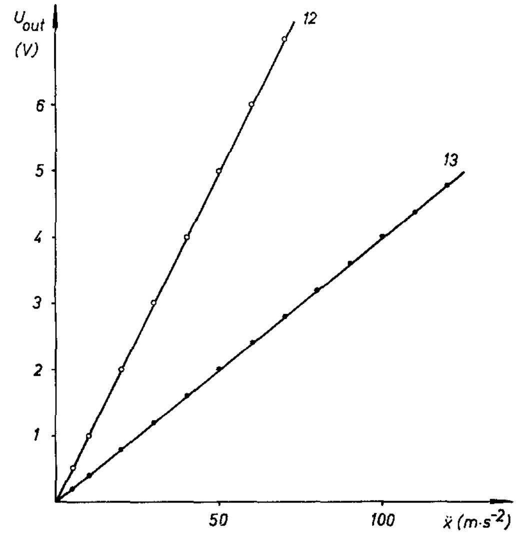

Fig. 3. The amplitude characteristics of electrocapillary acceleration meters.

The shapes of the frequency characteristics are in agreement with the concept for this type of acceleration meter. A proportionality to the amplitude was observed in the whole range studied. Acceleration meters working in short-circuit output conditions are characterized by a broader linearity range than the acceleration meters with an open-circuit output, owing to the elimination of the electrochemical impedance, Z_{el}, effect on the output short-circuit current. It was found by Figaszewski [11] that among the equivalent circuit elements, only the electrochemical impedance is, as a rule, characterized by the narrowest linearity range.

5. Conclusions

The experiments have confirmed the idea of a vibrational movement acceleration meter in which the output of the electrocapillary transducer is in a short-circuit state. Such acceleration meters do not have the main disadvantage of electrocapillary acceleration meters with an open-circuit output, i.e. a low-frequency limit of acceleration meter range which is determined by the properties of the electrocapillary transducer and whose value is rather high as mentioned in the Introduction. The low-frequency limit for linear characteristics of the acceleration meter working in short-circuit output conditions, is determined only by the frequency at which the electronic system attached to the transducer output is able to accomplish the conversion of a current signal into a voltage one and the integration. Transferring the problem of the low-frequency limit of acceleration meters to the construction of an outer electronic system makes it possible with the present possibilities of integrated operational amplifiers to set it as low as needed.

The second advantage of electrocapillary acceleration meters working under short-circuit conditions compared with their corresponding open-circuit systems is the broader linear range of dependence on acceleration amplitude.

The idea presented above, of a vibrational movement acceleration meter comprising an electrocapillary transducer and an outer electronic system playing the role of a current–voltage converter and an integrating system, may also be applied to the construction of an alternating pressure amplitude meter. A manometer based on the same idea will have the same advantages as the acceleration meter.

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