JOURNAL OF APPLIED ELECTROCHEMISTRY **16** (1986) 287–290

Electrocapillary sensing devices. VI. Displacement meters

ZBIGNIEW FIGASZEWSKI, ZBIGNIEW KOCZOROWSKI

Department of Chemistry, Warsaw University, Warsaw, Poland

Received 5 March 1985; revised 20 May 1985

The theory is presented of electrocapillary sensing devices of vibrational motion displacement amplitude resulting from the general equivalent circuit of electrocapillary transducers. Typical frequency characteristics are shown which confirm the theoretical considerations.

1. Introduction

In a series of papers published earlier [1–5] we have presented the theory, properties and possible applications of electrocapillary sensing devices, i.e. devices where the mechanical–electrical transduction is due to phenomena occurring at the mercury–electrolyte solution interface in a capillary. Electrocapillary sensing devices are systems consisting of a capillary 0.2–0.8 mm in diameter and 2–10 cm long filled with alternating mercury and electrolyte solution slugs. There are thus a number of mercury–solution interfaces in such a capillary. Thin wires inserted into terminal mercury slugs and sometimes into the central slug are the electric contacts. A mechanical factor acting on the device, e.g. capillary vibrations, provokes a charge flow in the device and generates an electric signal on its output terminals.

The basic applictions of the electrocapillary sensing devices are in vibration acceleration [1, 2, 5–7] or pressure [3, 4] amplitude measurements. The electrocapillary sensing devices described earlier worked in principle at frequencies lower than [1–3, 5–7] or equal to [4] the resonance frequency. The output of the sensing device can be either on open-circuit when a meter of high input resistance is connected to it [1–3] or in short-circuit conditions when it is connected to a current–voltage converter [5]. The open-circuit and short-circuit conditions of the electrocapillary sensing devices are defined by the electrical equivalent circuits [1, 5].

It is the purpose of this work to present and discuss a sensing device for vibration displacement amplitude working at frequencies higher than the resonance frequency. Such displacement meters operate under open-circuit output conditions.

2. Theory

The properties of electrocapillary transducers as functions of frequency can be presented in terms of the electric equivalent circuit (Fig. 1). This comprises an electrochemical impedance of interfaces, Z_{el}, a resistance of electrolyte solution, R_0, an alternating e.m.f. source, E, and a mechanical impedance composed of a resistance R_m, a capacity C_m and an inductance L_m. According to the assumed force–voltage analogy the mechanical impedance components R_m, C_m and L_m are electrical analogues of the mechanical model components, i.e. damping, stiffness and mass of the filling [1]. The electrochemical impedance, Z_{el}, contains the double layer capacity and the faradaic branch connected in parallel to it [2].

According to the general equivalent circuit (Fig. 1), an electrocapillary transducer can be applied to the displacement amplitude measurements over the frequency range above the resonance value, i.e. at $f \gg f_0$ if the impedance of the mercury–electrolyte solution interface consists mainly of a frequency-independent capacitance. In such conditions the general equivalent circuit of an electrocapillary trans-

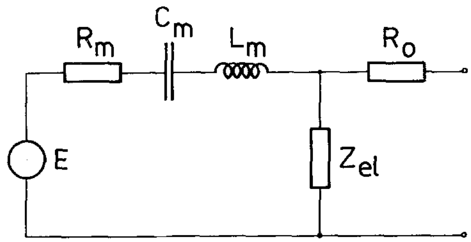

Fig. 1. Electrical equivalent circuit of an electrocapillary transducer.

ducer assumes the simple form presented in Fig. 2. The output voltage amplitude measured under open-circuit conditions, U_{open}, is expressed by the relationship;

$$U_{open} = E/(\omega^2 L_m C_{el} - 1) \tag{1}$$

Equation 1 can be simplified for higher frequencies,i.e. when the condition

$$\omega^2 L_m C_{el} \gg 1 \tag{2}$$

is fullfilled. Then the relationships [1]:

$$E = \propto F \tag{3}$$

$$F = m x_0 \omega^2 \tag{4}$$

$$L_m = \propto^2 m \tag{5}$$

yield

$$U_{open} = x_0/(\propto C_{el}) \tag{6}$$

In the above Equations, x_0 denotes the displacement amplitude of stimulating vibration, m denotes the mass of the capillary filling, F denotes the force acting on that mass by F, $\propto$ denotes the coefficient characterizing mechanical–electrical transduction which is constant for a given transducer and ω denotes the angular frequency.

Equation 6 indicates that the open-circuit voltage, U_{open}, is frequency-independant at a constant amplitude, x_0, of stimulating vibrations if Condition 2 is fulfilled. Therefore, electrocapillary transducers can be used for measuring displacement amplitudes. It may be concluded from Equation 6 that the open-circuit voltage does not depend directly on the mass of the capillary filling over the frequency range characteristic for a displacement meter.

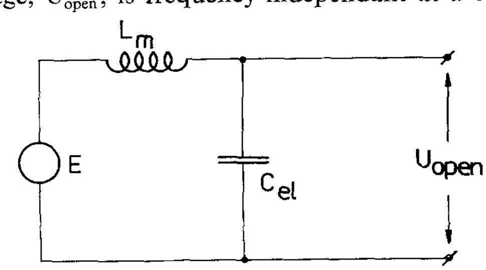

Fig. 2. Electrical equivalent circuit of an electrocapillary displacement meter.

The frequency beyond which Condition 2 is fulfilled depends on the L_m and C_{el} values and on the accuracy. Assuming e.g.

$$\omega^2 L_m C_{el} \gg 20 \tag{7}$$

and accepting typical values L_m and C_{el} [8], e.g. $L_m = 200\,\mathrm{H}$ and $C = 5\,\mathrm{nF}$, Condition 2 and hence Equation 6 are fulfilled above a frequency about 225 Hz.

According to Equation 6 the electrochemical impedance C_{el} must be frequency-independent for the open-circuit voltage to be a constant frequency function. The problem has been analysed in detail in an earlier paper [2] for acceleration meters. This analysis also applies to displacement meters. The electrochemical capacitance C_{el} can be made frequency-independent by eliminating the effect of the Warburg impedance, which may be achieved by ensuring a sufficiently low mercury ion concentration in the solution [2].

3. Experimental details

3.1. *Preparation of transducers*

The capillaries were filled with solution and then mercury slugs were inserted by means of a syringe. Mercury was removed from the terminal segments of the capillary with the syringe to leave air slugs of desired length. Platinum wires were then inserted into the terminal mercury slugs and the capillaries were sealed with a polyester resin. Before filling, the capillaries were cleansed by boiling with nitric acid (1 : 1). Triply distilled water was used to prepare the solutions. Sodium chloride was crystallized twice. The platinum wires were cleansed by etching with concentrated sulphuric acid and washing with water.

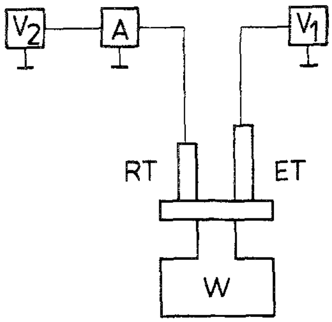

Fig. 3. Diagram of a measuring set.

3.2. *Apparatus*

Measurements were made using the apparatus presented in Fig. 3. Vibrations were generated by a vibrator made from a 10 W speaker fed by a sinusoidal vibration generator. The set-up presented in Fig. 3 additionally contains an electrocapillary transducer ET, a voltameter V_1, a reference piezoelectric transducer RT, an amplifier A and a voltmeter V_2.

4. Results and discussion

Typical frequency characteristics of electrocapillary displacement meters are shown in Fig. 4. The electrolyte compositions and the construction parameters of the displacement meters – the number of interfaces n, the capillary diameter ϕ, the mass of filling m and the lengths of air columns at the capillary ends ${}_1l_p$ and ${}_2l_p$ – are presented in Table 1. The sensing devices are numbered 14 and 15; the numbers are a continuation of the series described in the last paper [5].

At a constant displacement amplitude, the characteristics of transducers numbers 14 and 15 are flat from the frequencies of 400 and 700 Hz, respectively. No high-frequency limit was found over the range studied (up to 3000 Hz). The open-circuit voltage was proportional to the amplitude up to 100 μm, i.e. over the entire amplitude range studied.

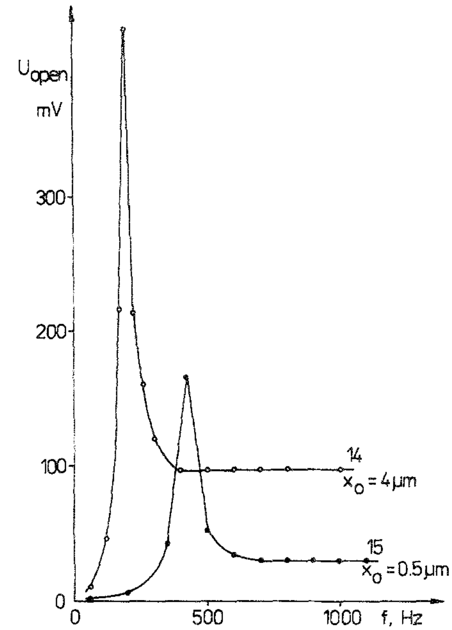

Fig. 4. Frequency characteristics of electrocapillary displacement meters.

The configuration making use of the short-circuit conditions has many advantages [5] but it cannot be applied to displacement meters. With the short-circuit conditions it is possible to eliminate the effect of impedance of the mercury–electrolyte solution interfaces on the output signal only in the case where the solution resistance is negligible compared with the impedance of the interfaces. This requirement is readily met at low frequencies, i.e. over the range where the electrocapillary transducers can be used as acceleration sensing devices. However, at the high frequencies at which displacement meters operate, the electrolyte resistance is

Table 1. Construction parameters of electrocapillary transducers

Transducer number	*Electrolyte composition*	*n*	ϕ *(mm)*	m *(mg)*	${}_1l_p$ *(mm)*	${}_2l_p$ *(mm)*
14	1.0 M H_2SO_4	8	0.44	15	0.75	0.75
15	1.0 M NaCl	20	0.38	30	0	0

generally comparable with the electrochemical impedance of the interfaces.

With the displacement meters, the conditions for eliminating the effect of the Faradaic branch impedance on the interface impedance are more advantageous than those existing in the acceleration meters. It has been demonstrated earlier [2] that a suitable increase in the Warburg impedance can be attained by employing a suitably low mercury ion concentration. In such a case the interface impedance consists of a frequency-independent capacitance of the electrical double layer.

References

[1] J. Kotowski, Z. Koczorowski and Z. Figaszewski, *J. Appl. Electrochem.* **10** (1980) 179.
[2] Z. Figaszewski, E. Kucharska-Giziewicz, K. Lisowska, J. Kotowski and Z. Koczorowski, *ibid.* **10** (1980) 185.
[3] Z. Koczorowski, E. Kucharska-Giziewicz and Z. Figaszewski, *ibid.* **10** (1980) 191.
[4] Z. Figaszewski, Z. Koczorowski and J. Mrówczyński, *ibid.* **10** (1980) 197.
[5] Z. Figaszewski, *ibid.* **12** (1982) 311.
[6] B. Podolsky, *US Patent No.* 2 735 949 (1956).
[7] A. Watanabe, *J. Electrochem. Soc.* **110** (1963) 72.
[8] Z. Figaszewski, Z. Koczorowski and S. Wydżga, *Messen Steuern Regeln* **19** (1976) 67.