# ON THE QUESTION OF MEASURING THE AMOUNT OF A MEDIUM IN A CLOSED VOLUME

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## Abstract

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# ON THE QUESTION OF MEASURING THE AMOUNT OF A MEDIUM IN A CLOSED VOLUME

Measuring the amount of a medium distributed in an arbitrary manner inside a vessel is an important problem. A new method is considered for measuring the amount, based on the resonance properties of systems in which, by means of metallic surfaces or lines placed inside the vessel, an electromagnetic field is formed whose frequency depends only on the ratio of the volumes of two media present in the vessel and differing in dielectric permittivities, and does not depend on the configuration of the boundary between them ([1]). The proposed system is applicable for measuring the amount of nonpolar and weakly polar dielectric media. The output characteristic of the system is the dependence of its resonant frequency on the amount (volume) of the medium being monitored.

It is known ([2]) that the frequencies of excited electromagnetic fields inside a closed region $V_0$, filled with two media having different dielectric permittivities, are determined by the relation

$$\omega - \omega_0/\omega_0 = (\varepsilon - \varepsilon_0) \int_{V_1} \dot{\mathbf{E}}\dot{\mathbf{E}}_0^* \, dV \Big/ \varepsilon_0 \int_{V_0} \dot{\mathbf{E}}\dot{\mathbf{E}}_0^* \, dV + \mu_0 \int_{V_0} \dot{\mathbf{H}}\dot{\mathbf{H}}_0^* \, dV, \qquad (1)$$

where $V_1$ is the volume of the measured medium with dielectric permittivity $\varepsilon$; $\dot{\mathbf{E}}_0$, $\dot{\mathbf{H}}_0$ are the vectors of the electric and magnetic field strengths in the region $V_0$ filled with a homogeneous medium with permittivity $\varepsilon_0$; $\omega_0$ is the frequency corresponding to this field; $\dot{\mathbf{E}}$, $\dot{\mathbf{H}}$ are the vectors of the electric and magnetic field strengths in the region $V_0$ filled with a medium of permittivity $\varepsilon$ in volume $V_1$ and a medium of permittivity $\varepsilon_0$ in volume $V_0 - V_1$; $\omega$ is the frequency corresponding to this field.

It follows from the formula that a sufficient condition for the independence of the frequency from the configuration of the filling region is the condition

$$(\varepsilon - \varepsilon_0) \int_{V_1} \dot{\mathbf{E}}\dot{\mathbf{E}}_0^* \, dV = A(V_1) \int_{V_0} (\varepsilon_0 \dot{\mathbf{E}}\dot{\mathbf{E}}_0^* + \mu_0 \dot{\mathbf{H}}\dot{\mathbf{H}}_0^*) \, dV, \qquad (2)$$

Fig. 1

Figure 1: Fig. 1

where $A(V_1)$ is some function of the volume $V_1$.

Physical realization of the sufficient condition (or of one close to it) can be carried out in various ways. Let us consider one of the possible ways of forming fields with prescribed properties.

Suppose that in a closed region $G$ (the region bounded by the surface of the vessel), filled with a homogeneous isotropic medium with permittivities $\varepsilon_0$, $\mu_0$, such a field with intensities $\dot{\mathbf{H}}_0$, $\dot{\mathbf{E}}_0$ is excited that, in the elementary cube $g$, the conditions

$$\int_g |\dot{\mathbf{E}}_0|^2 \, dV = A_1, \tag{3}$$

$$\int_g |\dot{\mathbf{H}}|^2 \, dV = B_1 \tag{4}$$

are satisfied for the neighborhood $g$ of any point belonging to the region $G$, where $A_1$, $B_1$ are constant quantities.

If the system is constructed in such a way that, when the parameters of the medium are changed to the values $\varepsilon, \mu = \mu_0$ in the region $g$, the field changes only in this region to the values $\mathbf{E}, \mathbf{H}$, while in the remaining part of the region $G/g$ the field has the same values $\mathbf{E}_0, \mathbf{H}_0$ (we assume that the boundary conditions are satisfied), then

$$\int_{G/g} \dot{\mathbf{E}}\mathbf{E}_0^* \, dV = \int_{G/g} |\dot{\mathbf{E}}_0|^2 \, dV; \tag{5}$$

$$\int_{G/g} \dot{\mathbf{H}}\mathbf{H}_0^* \, dV = \int_{G/g} |\dot{\mathbf{H}}_0|^2 \, dV; \tag{6}$$

$$\int_g \dot{\mathbf{E}}\mathbf{E}_0^* \, dV = A_2; \tag{7}$$

$$\int_g \dot{\mathbf{H}}\mathbf{H}_0^* \, dV = B_2 \tag{8}$$

for a neighborhood $g$ of any point belonging to the region $G$, where $A_2, B_2$ are constants.

**Fig. 1**

When these conditions are satisfied with an accuracy up to the approximation of the region $G$ and the region $P$ filled with the monitored medium of permeability $\varepsilon, \mu_0$ by elementary regions $g$, a sufficient condition is ensured for the resonance frequency to be independent of the configuration of the filling region for a given volume of it.

If

$$G \simeq \bigcup_{i=1}^{N} g_i; \qquad P \simeq \bigcup_{i=1}^{n} g_i,$$

then from the simultaneous solution of (1)-(8) we obtain:

$$\omega = \omega_0 \frac{\varepsilon_0[nA_2 + (N-n)A_1] + \mu_0[nB_2 + (N-n)B_1]}{\varepsilon_0[nA_2 + (N-n)A_1] + \mu_0[nB_2 + (N-n)B_1] + (\varepsilon - \varepsilon_0)nA_2} \tag{9}$$

or

$$\omega = \omega_0 f(n),$$

i.e., for a specified partition of the region $G$ into elementary regions $g$, the resonance frequency of the system depends only on the magnitude of the volume of the monitored medium.

Let us realize a system in which one can excite an electromagnetic field satisfying conditions (3)-(8).

Consider a uniform line in which filling with the measured medium is possible either from the ends of the line toward its middle or from the middle toward the ends (Fig. 1). The output characteristics depend on the distribution of the electric-field vector (or voltage) along the length of the line: the closer the voltage distribution function is to a constant value, the less the output characteristics differ from one another. By selecting certain boundary conditions at the ends of the line, it is possible to ensure the condition

$$|f_1(V) - f_2(V)| < \Delta \tag{10}$$

for any small $\Delta$, where $f_1(V), f_2(V)$ are the output characteristics when filling from the ends of the line toward its middle and from the middle toward the ends. For example, condition (10) is satisfied for a line loaded at the ends by an inductive resistance.

Assuming the distribution function of the electric field strength for a uniform line to be constant under the corresponding boundary conditions at the ···

Fig. 2

Figure 2: Fig. 2

ends, and neglecting the value of the magnetic-field energy in the filling region, the output characteristic can be calculated by formula (1). If the line is connected to a voltage source, then the field intensities have the values:

$$\mathbf{E}(x,y,z) = \begin{cases} M\mathbf{E}(x,y) & \text{in the region } V_0 \ (V_0 \text{ is the filling region}), \\ 0 & \text{in the region } V_k \ (V_k \text{ is the vicinity of the matching inductance}), \end{cases}$$

$M$ is a constant quantity;

$$\mathbf{H}(x,y,z) = \begin{cases} 0 & \text{in the region } V_0, \\ \mathbf{H} & \text{in the region } V_k \end{cases}$$

for any amount of filling.

The magnetic-field intensity is expressed in terms of the electric-field intensity from the condition of equality of the energies of the magnetic and electric fields at resonance.

Taking these conditions into account, we obtain

$$\omega = \omega_0 \frac{1}{\sqrt{1 + (\varepsilon_r - 1) z_1 / l}}, \tag{11}$$

where $l$ is the length of the line; $z_1$ is the sum of the lengths of the sections of the line filled with a medium having dielectric permittivity $\varepsilon$; $\varepsilon_r$ is the relative dielectric permittivity of the filling medium, $\varepsilon_r = \varepsilon / \varepsilon_0$.

Figure 1 shows the experimental curve (solid line) and the calculated one (by formula (11)) for $l = 0.75$ m, $\varepsilon_r = 1.8$, and initial frequency (determined by the value of the inductance at the ends) $\omega_0 = 40.5$ MHz.

The described properties of a line loaded at the ends by an inductive resistance can be used as the basis for constructing systems for measuring quantity under conditions in which the monitored medium occupies, in an arbitrary vessel, a region (simply connected or multiply connected) of any configuration.

A continuous metallic line distributed in the space of a metallic vessel so that in each elementary volume the length of its sections is the same forms an oscillatory system in which conditions (3)-(8) are satisfied with some approximation, provided that the ends of the line are loaded by an inductive resistance of not less than a certain value.

**Fig. 2**

An example of implementation of a quantity-measuring system for a vessel in the form of a rectangular parallelepiped is the system shown in Fig. 2, which has a measurement error not exceeding ±2%. (Figure 2 shows the maximum and minimum output characteristics.) The output characteristics were obtained for arbitrary positions of the vessel in space—

for the substance and for fillings in the form of elementary regions whose volume amounted to 1/10 of the total volume of the vessel.

In conclusion, we note that at the Institute of Automation and Telemechanics (Technical Cybernetics), quantity meters have been developed for typical vessel shapes, based on the principles set forth above. Experimental studies have shown that they have a measurement error within ±2%.

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*Note: Figure translations are in progress. See original paper for figures.*