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Abstract

Full Text

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APPLICATION OF CAVITY RESONATORS FOR LIQUID-LEVEL CONTROL

(Presented by Academician B. N. Petrov, July 6, 1962)

A metal tank, together with the liquid contained in it, may be regarded as a cavity oscillatory system capable of resonating at certain frequencies of electromagnetic oscillations excited in its interior. This system, like other circuits with distributed constants, has an infinite series of natural resonant frequencies. Their values depend on the dimensions of the conducting shells and on the features of the vessel's geometrical shape, on the height of the liquid level and its electromagnetic properties, and also on the structure of the excited field, which is determined by the position and number of standing waves.

If, during the measurement process, the dimensions of the vessel and the parameters of the liquid remain sufficiently stable, the tank can be used as a kind of sensor capable of changing its tuning depending on the level of the liquid contained in it ^(1,2). Converting the tank into a sensor is a fairly simple operation and does not require any substantial complication of the vessel design. For this purpose it is sufficient to install, in the resonant cavity, an antenna in the form of a pin or a loop of wire, which will serve as an element coupling the cavity resonator to the measuring circuit.

It is noted in the literature ⁽³⁾ that cavity resonators, in comparison with ordinary ones, have a very high Q , which, increasing with the geometrical dimensions, reaches, as experience shows, tens and hundreds of thousands. This quality is extremely important for accurate measurements of resonant frequency, and, in order to preserve it, the endovibrator method should expediently be used for measuring media that do not have large losses, i.e., good dielectrics or conductors. These include most petroleum-product derivatives, a number of organic compounds, liquefied gases, and molten metals. In such cases a cavity resonator, in comparison with known sensors, may have substantial advantages in stability and resolving power.

When applying the endovibrator method in practice, it must be borne in mind that the parameters of the sensing element depend on the parameters of the object in which the liquid level is to be measured; therefore, here one cannot construct the secondary instrument on the basis of averaged characteristics of a typical sensor. In each particular case it is first necessary to determine the frequency characteristics of the vessel (the dependence of resonant frequency on level), to choose from them the most suitable one, and then to match the

Fig. 1

Figure 1: Fig. 1

measuring circuit to it.

As an example, let us consider the frequency characteristics of a rectangular resonator. Taking into account the advantages of the method obtained in measuring liquids with small losses, we shall adopt, in formulating the problem, a mathematical idealization that simplifies the analysis and will be valid for two limiting cases most often encountered in practice. We shall assume that the conductivity of the resonator shell is infinite, and that the media filling its cavity have no electrical losses.

For a conducting liquid, the surface of the level may be considered as part of the shell forming the resonant cavity of the vessel. Actually—

the frequencies of this volume can be calculated by the known formula for a rectangular resonator⁴

$$\omega_{m,n,l} = \frac{1}{\sqrt{\varepsilon\mu}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{c}\right)^2};$$

here ε is the dielectric constant; μ is the magnetic permeability; a, b , and c are the length, width, and height of the resonant cavity of the vessel. If H_0 is the height of the vessel and H is the height of the level, then $c = H_0 - H$. For oscillations TE_{mnl} , $m = 0, 1, 2, \dots$; $n = 0, 1, 2, \dots$; $l = 1, 2, 3, \dots$, with $m = n \neq 0$. For TH_{mnl} , $m = 1, 2, 3, \dots$; $n = 1, 2, 3, \dots$; $l = 0, 1, 2, \dots$

Using this formula, characteristics corresponding to oscillations of the types TE_{101} and TE_{201} were calculated; they are shown in Fig. 1. As the level rises, the resonant frequency increases, tending to infinity. Obviously, not only a rectangular resonator, taken by us as an example, but also a resonator of any other shape will have a similar frequency characteristic, since in all cases the free volume of the vessel, i.e., the volume in which oscillations can exist, tends to zero as the level rises. This feature of the frequency characteristic for conducting liquids is important for practical applications of the method and precludes its use in the region of the upper level values. All means known in radio engineering that can be used to measure the tuning of a circuit have a limited frequency range; therefore, without additional switching devices in the secondary instrument, it will apparently not be possible to extend the measurement scale to more than 90% of the maximum level.

Fig. 1. Frequency characteristics of a rectangular vessel when filled with a liquid dielectric (solid lines) and an electrically conducting liquid (dashed lines). The dimensions of the circuit a, b , and H_0 are equal to 1 m.

When the resonator is filled with a liquid possessing the properties of a dielectric, the field lines are not bounded by the surface of the level and penetrate both the liquid and gaseous media. To construct the frequency characteristic, in this case it is necessary to solve the basic system of electrodynamic equations in rectangular coordinates⁵. Next, boundary conditions are applied on the surface separating the internal cavity from the external conducting space. Since the internal cavity of the resonator is divided into parts filled with different media, it is advantageous to seek the solution of the basic equations for each part of the volume separately. The extra constants of integration that arise in this procedure are subsequently eliminated with the aid of additional conditions requiring equality of the field components in adjacent regions on the interface between media. The idealization previously adopted in formulating the problem simplifies the analysis, making it possible to obtain fairly simple expressions in the form of two particular solutions, which may be considered separately.

For oscillations of the type TM_{mnl} , we shall have

$$\begin{aligned} \frac{1}{\varepsilon_1} \sqrt{\varepsilon_1 \mu_1 \omega^2 - \gamma^2} \operatorname{tg} [l\pi - (H_0 - H) \sqrt{\varepsilon_1 \mu_1 \omega^2 - \gamma^2}] = \\ = \frac{1}{\varepsilon_2} \sqrt{\varepsilon_2 \mu_2 \omega^2 - \gamma^2} \operatorname{tg} H \sqrt{\varepsilon_2 \mu_2 \omega^2 - \gamma^2}, \end{aligned}$$

where

$$\gamma^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2.$$

For TE_{mnl} oscillations

$$\frac{\mu_1 \operatorname{tg} [l\pi - (H_0 - H) \sqrt{\varepsilon_1 \mu_1 \omega^2 - \gamma^2}]}{\sqrt{\varepsilon_1 \mu_1 \omega^2 - \gamma^2}} = \frac{\mu_2 \operatorname{tg} H \sqrt{\varepsilon_2 \mu_2 \omega^2 - \gamma^2}}{\sqrt{\varepsilon_2 \mu_2 \omega^2 - \gamma^2}}.$$

In the formulas, the subscript 1 refers to the gaseous medium, and 2 to the liquid.

Returning again to Fig. 1 and comparing the obtained characteristics with the preceding ones, we note the coincidence of the initial points corresponding to an empty vessel. As the level rises, the resonant frequency of the vessel with the dielectric decreases, tending toward the value $f_0/\sqrt{\varepsilon\mu}$ (f_0 is the frequency of the tank without liquid). Since for most nonpolar dielectrics ε lies within the range 1.5-2.5, while the magnetic permeability differs negligibly from unity, the change in frequency at the limiting points when the tank is filled with liquid will reach 25-60%. This ratio of limiting frequencies remains valid for all other characteristics of the sensor, which correspond to a series of higher harmonics of the resonator, and also for all tanks regardless of their configuration.

In the experimental investigation of the method, cylindrical, coaxial, and spherical vessels made of copper, brass, aluminum, and stainless steel were used. The vessels were filled with gasoline, kerosene, transformer oil, liquid nitrogen, and oxygen; that is, in all cases the liquid media had the properties of good dielectrics. The resonant frequencies were determined from a standard-signal generator at the moment when the maximum current passed through the detector connected to the resonator. To measure small changes in the tuning of the resonator (for example, due to the influence of temperature), a frequency-sensor circuit was used in which the vessel served as the master circuit of a sinusoidal-oscillation generator. The signal of the frequency sensor, by the beat method, was compared with the signal of a reference generator.

Let us note the principal results of the study.

1. It was found that the experimentally obtained frequency characteristics agree well with the data obtained theoretically (within several percent). This circumstance testifies in favor of the idealization we adopted in calculating the natural oscillations of the vessel.
2. Surface disturbance of the liquid and tilting of the vessels, within certain limits depending on the shape of the tank and the structure of the excited field, have a negligibly small effect on the resonant frequency, which makes it possible to use the endovibrator method for nonstationary objects and during boiling of the liquid.
3. The errors in measuring the level of liquid dielectrics by the endovibrator method are, in character and magnitude, close to the family of errors of capacitive methods. However, because of the high resonant properties of volume circuits, the endovibrator method makes it possible substantially to reduce the magnitude of the errors introduced by the measuring circuit.

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