

Influence of structural parameters on instrumental error of electromagnetic log sensor

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Abstract. Instrumental error of an electromagnetic log sensor at depths of more than one kilometer is studied. Operating principle of the electromagnetic sensor is shown and a mathematical model is developed. Analysis of sensor-registered speed dependence on external hydrostatic pressure is presented. It is demonstrated that an additional instrumental error occurs in the electromagnetic sensor due to the structure deformation during deep-sea submersion. It has been found that the value of relative error depends on design parameters and operational conditions of the sensor. It is shown that even when deep-sea vehicles travel at a low speed, the error caused by external hydrostatic pressure can make up a significant portion of the instrumental error and should be taken into account during operation. The design parameters of the sensor, affecting its instrumental error are determined. The influence of temperature on this error is studied. The ratio of design parameters at which the instrumental error does not exceed the permissible value is identified.

Introduction

The instrumental errors of an electromagnetic log sensor (hereinafter sensor) can be divided into methodological errors related to the method of measurements, and instrumental errors caused by environmental effects. Different types of these errors, the causes for their occurrence, and the methods of their control are rather fully described in [1–4].

When designing sensors for deep-sea vehicles operating under high hydrostatic pressure (HP) (up to 60 MPa), it is essential to provide for required rigidity and durability of their structural elements. Since the rigidity and durability are finite, the HP effect leads to certain deformations, the magnitude of which is proportional to pressure. The deformations cause relative motion of the structural elements due to the difference in their physical and mechanical characteristics (heterogeneity of the structure), which induces an additional instrumental error. Its magnitude depends on the structural parameters (SP) and the operation conditions of the sensor. This kind of the sensor error does not have a significant effect on the log measurements at small depths or during surface operations, so it was not taken into account previously. However, during deep water operations, e.g. submersions to 6 km, and with a certain ratio of SP of the sensor, the said error can reach several percent and needs to be taken into account [5].

This work deals with the analysis of the SP influence on the instrumental error caused by high HP.

1. Hydrostatic pressure influence on the sensor's error

While operating the sensor under the effect of external HP and temperature fluctuations, its structural elements experience deformations, so that their relative position changes. Due to the relative



displacement of the structural elements, electrodes in particular, the electromagnetic characteristics of the sensor change, thus leading to the sensor readings alteration. Relative displacements of the elements depend on the finite rigidity of the structure and cause additional instrumental error of the sensor. Relative error δV of the sensor, represented in Fig. 1, depends on HP and is written as follows [5]:

$$\delta V(P) = 1 - \left(\frac{R^2 + \left(l_1 \left(1 - \frac{P}{E_1} \right) + l_2 \left(1 - \frac{P}{E_2} \right) \right)^2}{R^2 + (l_1 + l_2)^2} \right)^{1,5}, \quad (1)$$

where P is hydrostatic pressure, Pa; E_1 is Young's modulus of the electrode material, Pa; and E_2 is Young's modulus of compound, Pa.

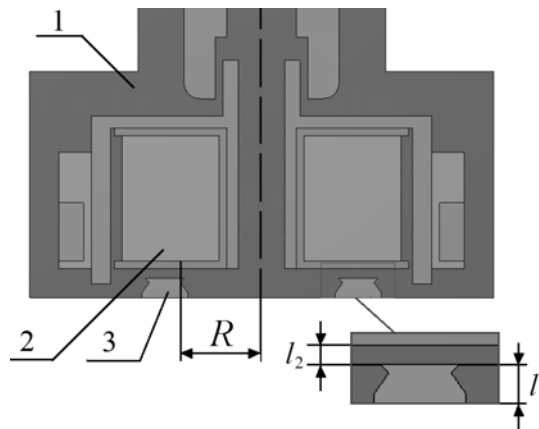


Fig. 1. Electromagnetic log sensor structure 1 – compound; 2 – coil; 3 – electrode; R – medial radius of the inductor; l_1 – electrode height ; l_2 – compound layer height under the electrode.

It follows from the expression (1) that the relative error of the sensor caused by the structure deformations depends on the HP value (P) and the sensor SP such as dimensions of its elements (R , l_1 , l_2) and properties of the materials used (E_1 , E_2).

Some values of the sensor relative error calculated according to the expression (1) for different values of the parameters R , l_1 , l_2 are given in Table 1. Calculations were done with the HP value $P = 60$ MPa, which is equivalent to submersion depth of 6 km.

Table 1. Values of relative error of the sensor with varying structural parameters

R , mm	l_1 , mm	l_2 , mm	δV	R , mm	l_1 , mm	l_2 , mm	δV
2	2	2	0.247	10	2	2	0.0043
2	2	5	0.0397	10	2	5	0.0142
2	5	2	0.0172	10	5	2	0.0061
2	5	5	0.0296	10	5	5	0.0154
5	2	2	0.0121	15	2	2	0.0021
5	2	5	0.285	15	2	5	0.0077
5	5	2	0.0124	15	5	2	0.0033
5	5	5	0.0247	15	5	5	0.0095

The results show that with certain ratio of SP values, the relative error can reach up to several percent. To demonstrate the dependence of the relative error of the deformed sensor on the SP, the expression (1) can be rewritten as follows:

$$\delta V(X) = 1 - \left(\frac{1 + (n(1-X) + m(1-kX))^2}{1 + (n+m)^2} \right)^{1.5}, \quad (2)$$

where $k = \frac{E_1}{E_2}$, $X = \frac{P}{E_1}$, $n = \frac{l_1}{R}$, $m = \frac{l_2}{R}$.

The easiest way to minimize the relative error δV at the design stage is to vary the SP n and m . The parameters n and m are above zero, and partial derivatives $\frac{\partial}{\partial n} \delta V$ and $\frac{\partial}{\partial m} \delta V$ do not turn to zero simultaneously. This means that the function (2) has no extrema at real values of the SP n and m .

After Maclaurin expansion of the expression (2), confining ourselves to the first order of smallness, we obtain:

$$\delta V(X) \approx 3X \frac{(n+m)(n+km)}{1+(n+m)^2}. \quad (3)$$

At the HP value $P = 60$ MPa, the relative errors calculated according to the expressions (2) and (3) differ by no more than 2%. This confirms the possibility of using the expression (3) for practical calculations.

The dependence of the sensor's relative error on the SP n and m at $E_1 = 8 \cdot 10^{10}$ Pa and $E_2 = 3 \cdot 10^{10}$ Pa with $X = 3.75 \cdot 10^{-4}$ (the HP is 30 MPa, the depth is 3000 meters) and $X = 7.5 \cdot 10^{-4}$ (the HP is 60 MPa, the depth is 6000 meters) is shown in Fig. 2.

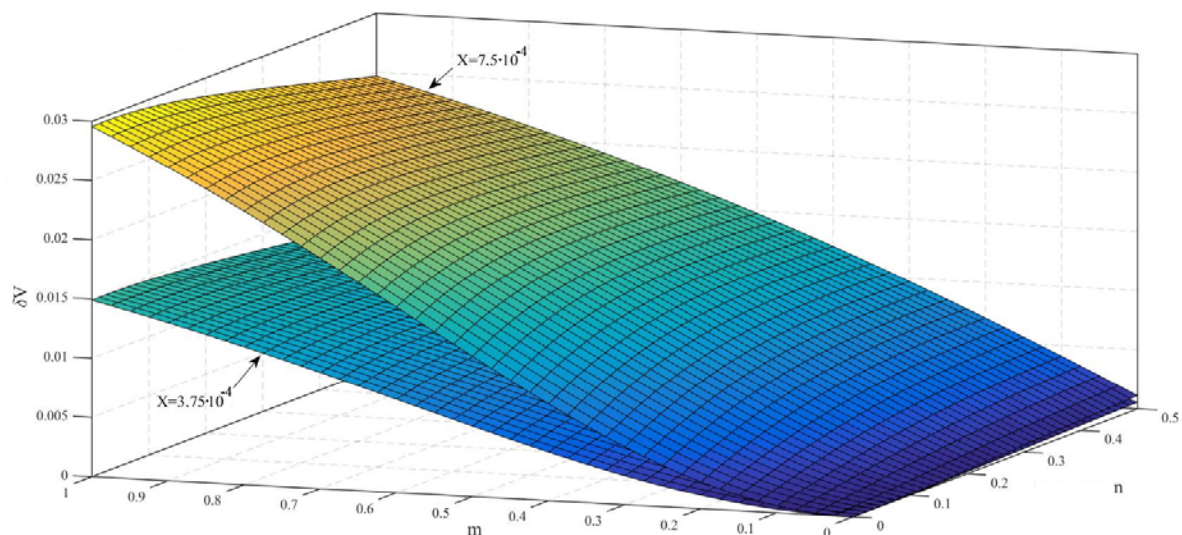


Fig. 2. Dependence of the relative error of the sensor on structural parameters.

Figure 2 shows that the relative instrumental error of the sensor, caused by external HP significantly depends on the change in the parameter m which describes the thickness of the insulating compound, and at a certain ratio of SP, it reaches up to 3%.

The instrumental error of speed measurement stated in the technical specifications of the electromagnetic log LEM 2-1M is ± 0.1 knots in the speed range from minus 6 to 50 knots [6]. For example, at the speed of 5 knots, an error of 0.1 knots leads to a relative error of 2%. As has been

shown by numerical modeling with the use of analytical expressions, an additional error of the sensor, caused by HP is comparable to the instrumental error of this sensor. At high motion speeds, the error of the sensor, caused by the deformation of contact area could become prevailing. However, even theoretically, the assumption that in the foreseeable future deep sea vehicles will be able to move at a high speed under high HP is too optimistic.

2. Thermal influence estimation

In addition to the deformations caused by the mechanical effect of HP, the structure sustains deformations due to the environment temperature changes. Since the structure is symmetrical, it is acceptable to determine the displacement Δz of electrodes in the plane shown in Fig. 1, using the coefficient of thermal expansion. In this case, the displacement of electrodes $\Delta z = l_1 + l_2$ consists of the mechanical and thermal deformations the values of which can be determined as:

$$\Delta z(t) = (\alpha_1 l_1 + \alpha_2 l_2)(t - t_0), \quad (4)$$

where α_1 is the coefficient of thermal expansion for the electrode material, K^{-1} ; α_2 is the coefficient of thermal expansion for the compound, K^{-1} ; t_0 is normal temperature, K; and t is current temperature, K.

The current temperature range from 273.15 K to 308.15 K (0–35° C) is taken for calculations based on the real operational conditions of the sensor.

Considering the formula (4), the expression (1) for the relative error of speed measurement takes the form

$$\delta V(P, t) = 1 - \left(\frac{R^2 + \left(l_1 \left(1 + \alpha_1(t - t_0) - \frac{P}{E_1} \right) + l_2 \left(1 + \alpha_2(t - t_0) - \frac{P}{E_2} \right) \right)^2}{R^2 + (l_1 + l_2)^2} \right)^{1,5}. \quad (5)$$

In considered range of temperatures t , the Young's modulus of metals changes by less than 1% [7, 8], and the change of elastic modulus of epoxy resin E-20 (basic component for most of epoxy compounds) is no more than 3 % [9]. Therefore, the change of elastic modulus of the materials can be ignored.

Considering the parameters introduced in (3), the expression (5) can be rewritten as follows:

$$\delta V(P, t) = 1 - \left(\frac{1 + (n(1 + \alpha_1 \Delta t - X) + m(1 + \alpha_2 \Delta t - kX))^2}{1 + (n + m)^2} \right)^{1,5}, \quad (6)$$

where $\Delta t = t - t_0$ is the temperature change, K.

The effect of thermal deformations on the sensor's error can be estimated by the parameter

$$\gamma = \frac{V(P)}{V(P, t)}. \quad (7)$$

Substituting (3) and (6) into (7), we get

$$\gamma = \left(\frac{1}{1 + (D + F \cdot \Delta t)^2} + \frac{D^2}{1 + (D + F \cdot \Delta t)^2} \right)^{1,5}, \quad (8)$$

where $D = n(1 - X) + mn(1 - kX)$; $F = (n\alpha_1 + m\alpha_2)$.

The parameters α_1 и α_2 have the order of 10^{-5} and lower for the materials used in the structure. The parameters n and m do not exceed the value of 10 in real structures. With such values of α_1 , α_2 , n and

m , the parameter F does not exceed the value of 10^{-4} . This suggests that the parameter F can be considered small. Using Maclaurin expansion of the expression (8) based on F , and confining ourselves to the first degree of smallness, we obtain:

$$\gamma \approx 1 + 3F \cdot \Delta t \frac{D}{D^2 + 1}. \quad (9)$$

The maximum value of the parameter γ is limited to 0.9 at real values of the parameters n , m , k and Δt . Therefore, the relative error of the sensor, considering only mechanical deformations differs by no more than 10% from the relative error considering additionally the thermal deformations. This indicates a small influence of thermal deformations on the error of the sensor in real structures.

3. Instrumental error estimation

In course of design, one of the basic requirements for the sensor is an allowable error, the maximum value of which is usually limited by the requirement specifications and determined on the basis of the required operating conditions and tasks of a deep-sea vehicle. A relatively simple check of the sensor error magnitude is possible only while the vehicle is in the surface position. In this case, obviously, the sensor is not affected by the increased HD and, therefore, the instrumental error caused by the deformation of the structure cannot be taken into account.

In order to keep the error of the sensor within the allowable limits during deep sea operations, the following condition should be fulfilled:

$$\delta V_0 + \delta V(P) \leq \delta V, \quad (10)$$

where δV is the allowable value of the sensor's error; δV_0 is the value of the sensor's error at the water surface; and $\delta V(P)$ is the value of the error caused by the sensor deformations due to HP.

Let $\delta V = \psi \cdot \delta V_0$, where ψ is a constant safety factor derived from the technical requirements. Then the fulfillment of the condition (10) will be written as follows:

$$\delta V(P) \leq \delta V_0(\psi - 1) \quad (11)$$

Considering (3), the requirement for the SP can be derived, the fulfillment of which ensures that the sensor's readings will change within the specified limits:

$$3X \frac{(n+m)(n+km)}{1+(n+m)^2} \leq \delta V_0(\psi - 1). \quad (12)$$

By introducing $x = \frac{m}{n} \geq 0$, the relation (12) takes the form

$$n \leq \sqrt{\delta V_0 \frac{\psi - 1}{3X(1+x)(1+kx)} \left[1 - \frac{\delta V_0(\psi - 1)(1+x)}{3X(1+kx)} \right]}. \quad (13)$$

Near the water surface, vast majority of sensors have an instrumental error ΔV_0 equal to ± 0.1 knots. The speed of vehicles operating ultradeep does not exceed 5 knots [11, 12]. In this case, the value of the absolute error ΔV_0 corresponds to the value of the relative error δV_0 equal to 0.02-0.017.

As an example, we consider a sensor with the parameters $k=26$, $\delta V_0=0.02$ operating in the conditions determined by the parameter $X = 7.5 \cdot 10^{-4}$; the safety factor ψ is taken equal to 1.05 (allowable excess is 5%). In this case, the area of allowable values for the SP n and x is shown in Fig. 3.

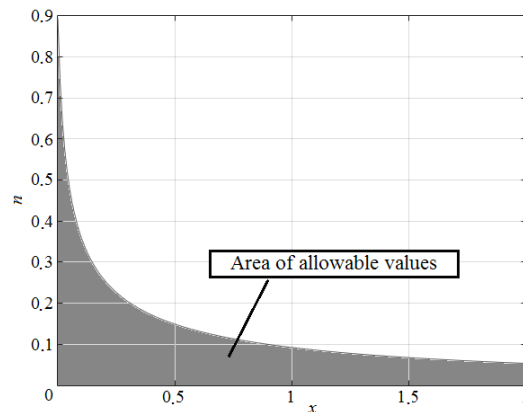


Fig. 3. Area of allowable values of structural parameters n and x at $k=26$; $\delta V_0=0.02$; $X=7.5 \cdot 10^{-4}$; $\psi=1.05$.

If the parameter k is varying, the area of allowable values of the SP is limited by the surface (Fig. 4).

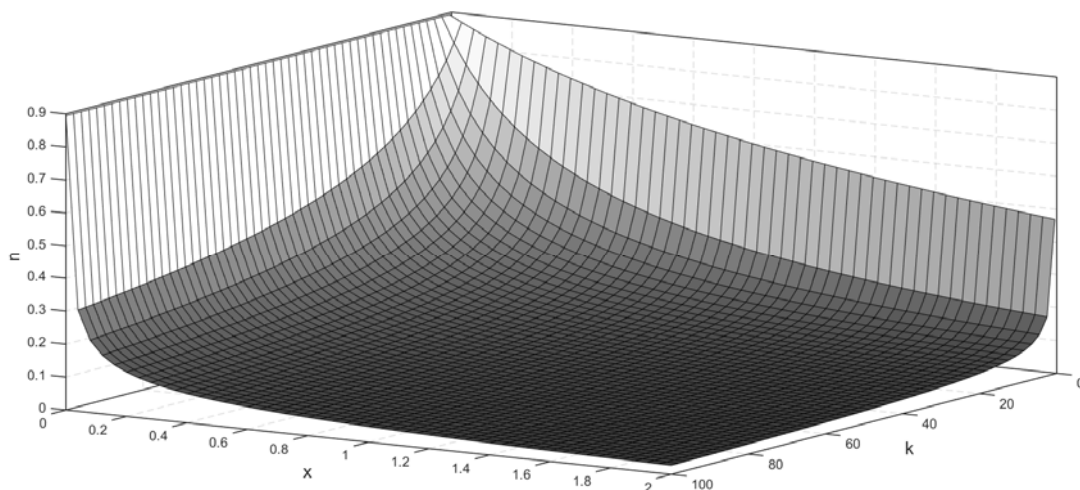


Fig. 4. Area of allowable values of structural parameters n , x and k at $\delta V_0 = 0.02$; $X = 7.5 \cdot 10^{-4}$; $\psi = 1.05$.

The expression (13) makes it possible to choose the ratio of the sensor's SP at which the instrumental error of the sensor, which takes into account the structure deformation caused by HP, does not exceed the allowable value. Thus, using the expression (13), the error of the sensor, caused by the effect of HP, can be taken into account as early as at the design stage.

Conclusions

An additional instrumental error of the electromagnetic log sensor has been determined, which occurs under exposure to external hydrostatic pressure and depends on the finite rigidity of the structural elements. Analytical expressions have been derived, which make it possible to estimate the level of the sensor error under conditions of varying stress-strain state. It has been shown that with certain ratios of the structural parameters, the discussed error reaches a value of more than 3%. It has been found that temperature fluctuations within the acceptable range do not make a significant contribution in the error variations. An expression has been presented, which allows the ratio of structural parameters under given operating conditions to be chosen so as to ensure that the instrumental error does not exceed the allowable value. Knowing the dependence of the instrumental error of the sensor on the magnitude of the external hydrostatic pressure, it is possible to work out a correction to the sensor readings depending on the submersion depth.

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