Implementation of automation in vibration-isolating supports of new type for engines of sea and river vessels

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Abstract. In almost all areas of modern technology, the problem of vibration isolation arises, which is associated with the goal of improving the quality, reliability and productivity of various technical objects. One of the important tasks of shipbuilding is to reduce vibration levels of ship power equipment. This article proposes a non-linear control law for an electromagnetic hydraulic vibration-insulating support (EGVO) for ship power plants (SEP), which allows you to compensate for external harmonic disturbances at the SEP, which leads to an increase in their technological safety. The proposed control law of EGVO has advantages over various control laws of vibration-insulating systems of an active type for SEP. The proposed method can be used to create vibration-isolating active systems for various technical objects. The essential novelty of this method is a consistent synthesis of control laws and the creation of a single process of technological self-organization and control.

1. Introduction
The problem of vibration protection arises in almost all areas of modern technology and is closely related to the need to reduce the level of vibration and shock in order to improve the quality, reliability and productivity of machines and devices.

A particularly serious situation in the field of vibration protection has developed on water transport vessels. Numerous studies have reliably established that on ships of the fleet for various purposes, the vibration of the hull often exceeds the norm, so the task of protecting the ship and crew from the negative effects of vibration is still relevant. Hence, reducing the vibration levels of ship power equipment is the most important task of shipbuilding.

Currently, an independent direction in the field of depreciation of marine equipment, which can be called passive-active vibration isolation systems, is beginning to actively develop [1-3].

The electrohydraulic vibration isolation support (EGVO) uses a combination of a passive vibration isolation system and an active stabilization system for the protected object. The need for high static rigidity determines the use of the hydraulic system. The active vibration protection part is made in the form of electromagnetic springs-inductors. The correct combination of the parameters of the support parts allows you to meet the requirement of high rigidity for static load and low rigidity for vibration. Thus, a new quality is realized in one device, which is unattainable in passive and active systems [4].

The advantages of EGVO include stability of characteristics, high speed, compatibility with elastic shock absorbers, as well as the possibility of significant lateral displacements of the mobile platform relative to the vibration-insulating base [1, 4].
2. Description model of EHVO

The electro-hydraulic vibration isolation support (figure 1) contains a cargo platform 1 made of carbon soft magnetic steel on which a vibration damping object is installed (for example, a ship engine), and which is connected by a central rod 2 with a hydraulic piston 3 made of ferromagnetic corrosion-resistant steel. The hydraulic piston 3 is equipped with throttling holes 4 and end seals 5. The hydraulic piston 3 is placed in the cylinder 6. In the upper and lower parts of the rod 2 there are inductance coils 7 with poles 8, separated from the cylinder 6 by covers 9. Rod 2, piston 3, cylinder 6, coils 7 are placed in housing 10, which plays the role of a magnetic circuit, and rod 2 plays the role of an anchor. The armature 2 has the ability to move in the axial direction inside the tubes 11. Between the rod 2 and the body 10 there is a support spring 12. The covers of the hydraulic cylinder 9 and the body of the support 10 have elastic rubber seals 13, fixed by vulcanization. The buffer cavity 14 is connected to the pump 15, a control valve 16 is located in the outlet duct of the buffer cavity (figure 2). The main task of the control circuit is to alternately supply current to the inductors 7, depending on the signal from the sensor 17. The device operates as follows. The pump 15 supplies the working fluid to the buffer cavity 14, in which a constant pressure is maintained by the control valve 16. A change in the load on the cargo platform 1 causes the movement of the central rod 2 with the hydraulic piston 3.

![Figure 1. Schematic diagram of EHVO.](image1)

The throttling holes 4 of the hydraulic piston 3, when it is moved, contribute to the flow of liquid from the buffer cavity 14 to the over-piston space and back, so the over-piston space plays the role of a damper. In turn, the movement of the rod 2 catches the sensor 17, the output signal of which is fed through the control unit 16 to the input of the power supply unit 19. The power supply unit 19 supplies the current of the required value either to the upper inductor 7 or to the lower one. The electromagnetic field of the inductors 7 acts on the rod 2 in the direction necessary to smooth out the vibrations. Thus, the inductor 7 also acts as an elastic element.

The use of inductors 7 in the construction of a vibration-insulating support allows a computer to be used with a high degree of accuracy to control the support, since electromagnetic drives are widely used in almost all industries and are very convenient for this purpose.
3. Calculation of the working process of the electromagnetic component of the EGVO
From the description of the EGVO, it follows that the electromagnetic actuator of the vibration-isolating support is an electromechanical device, one of the defining components of which is electromagnets that perform mechanical work to drive a hydraulic piston, or hold it stationary, or perform both operations sequentially. In the EGVO, the magnetic flux, branching, passes not only into the “collar” of the magnetic system, but also into the space between the electromagnets and into the magnetic core of the neighboring system, crossing part of the turns of its coil. We calculate the flux coupling of the mutual induction of each of the electromagnets and evaluate its influence on the nature of the electromechanical transients.

Let us assume that the nonlinearity of the magnetization curve is neglected, since taking into account the reciprocity of induction, with strong saturation of steel, will significantly complicate the calculation; the magnetic resistance of the yoke of an unexcited electromagnet is neglected [2,5]. Suppose that the working stroke electromagnet in the EGVO is turned on and the maximum value of its flow is equal to $\Phi_0$.

Figure 3 shows what $\Phi_0$ passes from the yoke to the anchor along the pole 1, the space between the electromagnets 2, the "collar", the pole of the neighboring electromagnet 3 and through its coil along the paths 4-6.

![Figure 3. Scheme for calculating the mutual induction of EGVO coils.](image)

Magnetic conductivity of each of the non-working gaps, taking into account the eccentricity:

$$G_a = \pi \eta_a \mu_0 \frac{2K}{\sqrt{\Delta^2 - e^2}}.$$ 

Magnetic conductivity of the space between electromagnets in the EGVO:

$$G_{12a} = \pi \eta_a \mu_0 \frac{2l_{12}}{\ln \frac{r_{2a}}{r_{1a}}}.$$ 

Magnetic conductivity of the space 4 between the armature and the yoke of the idling electromagnet is $G_{4a} = g_a h_{4a}$, where: $g_a$ is specific magnetic conductivity, $g_a = \frac{2\pi \mu_0}{\ln \eta_1}.$

For the magnetic flux paths 5, 6, we have: $G_{01a} = G_{5a} + G_{6a} = \pi \mu_0 \eta_{1a} G_{01},$ where
\[ G_{01} = 0.54 + \frac{n}{2} + 1.27 \left( \eta - \sqrt{\eta (\eta - 1)} \right) \cdot \ln \frac{n}{\eta - 1}. \]

The magnetic flux passing into the no-load electromagnet is defined as
\[ \Phi_{12} = \Phi_0 \frac{g_a h_0 + G_{01a}}{2G_a + G_{12a} + g_a h_0 + G_{01a}}. \]

Magnetic tension between anchor and yoke \[ U_a = \frac{\Phi_0}{2G_a + G_{12a} + g_a h_0 + G_{01a}}. \]

The magnetic flux of mutual induction as a function of the x coordinate is expressed as
\[ \Phi_{xa} = \left( g_a h_0 + G_{01a} \right) U_a - g_a x_a \cdot U_a. \]

We define the flow coupling of mutual induction, taking into account the assumptions made, as
\[ \Psi_{12a} = \frac{1}{l_1} \int_0^{l_{ya}} \frac{1}{g_a} U_a \left( \frac{1}{2} g_a h_0^2 + G_{01a} h_0 \right), \] where \( w_1, l_{ya} \) values correspond to the idling coil. Converting the obtained formula, we obtain the mutual induction flow coupling with the working stroke electromagnet turned on:
\[ \Psi_{12a}' = \pi r_{ya}^2 B_{0y} w_1 \Psi_{12}, \] where:
\[ \Psi_{12} = \frac{1}{l_1} \frac{1}{2} B_2 \left( \frac{h_1^2}{\ln r_1} + G_{01} h_1 \right). \]

Similarly, when the no-load electromagnet is switched on \[ \Psi_{21a}' = \pi r_{ya}^2 B_{0y} w_2 \Psi_{21}, \] where:
\[ \Psi_{21} = \frac{1}{l_1} \frac{1}{2} B_1 \left( \frac{h_2^2}{\ln r_2} + G_{02} h_2 \right). \]

When the electromagnets are switched on with the same name \( \Psi_I = \Psi_1 \pm \Psi_{12}, \Psi_{II} = \Psi_2 \pm \Psi_{21}, \) where \( \Psi_I, \Psi_{II} \) are flow coupling of the coils of the electromagnets of the idle and working stroke; the plus and minus signs correspond to the consonant and counter inclusion of the windings.

Let us consider an example of calculating the mutual induction of EGVO coils taking into account the mutual induction of electromagnets without taking into account the influence of pole resistance and non-working gaps. Neglecting the discharge current of the capacitance \( R_p >> R_f, \) we imagine the following field blanking scheme (fig. 4) [5].

The movement cycle is divided into 4 intervals [2]. When the no-load electromagnet is switched on, in all the functions included in the equations, we use \( h_1 \), when the working stroke electromagnet is switched on \( h_2 \). Therefore, the unknown quantities in the equations are \( B_1, B_2, h_1 \) or \( B_1, B_2, h_2 \).

The equation of the electric equilibrium of an electromagnet connected to a quenching circuit in relative terms has the form:
\[ \Pi_1 \frac{n+1}{n-1} f_1 + \Pi_2 \frac{d \Psi}{dt} + \Pi_4 l f_1 \int_0^t df + \Pi_5 I f = 0, \]
where \( \Pi_4 = \frac{r_{ya}^2}{C_{wE}} \sqrt{\frac{\gamma}{\mu_0}}; \quad \Pi_5 = \frac{r_{ya}^2 B_0 R_f}{\mu_0 w E}. \)
Figure 4. Field quenching circuit of the electromagnet coil in the EGVO.

Since in the EGVO the value of the magnetic conductivity of the non-working gap $G_d$ slightly exceeds the conductivity of the working gap, reducing the $G_d$ causes a shift of the neutral and a decrease in the thrust force, as follows from the obtained dependencies. On the other hand, with a large value $G_d$ the mutual induction flux is small. Therefore, in a properly designed EGVO, the phenomenon of mutual induction does not have a noticeable effect on the nature of electromechanical transients. Calculations carried out on a computer without taking into account and taking into account mutual induction and obtained by equations confirm this conclusion.

Thus, the calculation of the static characteristics of electromagnets is carried out, which plays a decisive role for the derivation of equations describing the dynamic processes of the magnetic circuit of the EGVO.

4. Mathematical model and sequential synthesis of the EHVO control law

Despite the seeming simplicity of the design and principle of operation, the calculation of EHVO is a rather complex problem, the solution of which is associated with a number of difficulties due to the specific features of electromagnetic devices, since their calculation is associated with a large number of factors and limitations.

Let us represent the mathematical model of EHVO in the following form [1]:

$$\frac{dx_1(t)}{dt} = -ax_1 + bu,$$
$$\frac{dx_2(t)}{dt} = -\alpha_1 x_2 - \alpha_2 x_3 - \frac{1}{M} F(x_1) + \frac{1}{M} f(t) - g,$$
$$\frac{dx_3(t)}{dt} = x_2,$$
$$y = \gamma x_3 + F(x_1) - mg,$$

where $x_1$ – electromagnet current; $x_2, x_3$ – speed and position of the moving platform; $F(x_1) = \beta_0 x_1^2$ – driving force; $f(t) = A \sin \omega t$; $M_0, M_1$ – persistent disturbances due to gravity; $\beta_0$ – object electrical circuit parameter.

The control problem is to suppress the influence of disturbances, therefore, to fulfill the condition:

$$y = \gamma x_3 + F(x_1) - mg \leq \varepsilon,$$

where $y$ is the quantity proportional to the force acting on the base, $\varepsilon$ is infinitesimal.

The main goal of constructing an EHVO is to minimize the value $y$ [1, 4].
To solve the formulated problem of EHVO control based on (1), we construct an extended synthesis model:

\begin{align*}
\frac{dx_1(t)}{dt} &= -\alpha x_1 + bu, \\
\frac{dx_2(t)}{dt} &= -\alpha_4 x_2 - \alpha_2 x_3 - \frac{1}{M} F(x_1) - z(t), \\
\frac{dx_3(t)}{dt} &= x_2, \\
\frac{dz(t)}{dt} &= y, \\
\end{align*}

(3)

where \( z \) is an introduced additional variable designed to suppress external disturbances \( f(t) \).

According to the structure of the extended synthesis model (2), to construct the control law \( u \), it is sufficient to use the introduction of two sequential invariants. First of all, we introduce the macro variable:

\[ \psi_1 = \sqrt{\beta_\rho} x_1 + \sqrt{x_4}, \]

(4)

where \( x_4 \) is some additional variable that reflects «internal» control; \( \beta_\rho \) is a regulator parameter. Then, substituting \( \psi_1 \) into the first invariant relation:

\[ 0) \psi_1 + \psi_1 = tT, \]

(5)

we get the expression:

\[ \sqrt{\beta_\rho} \dot{x}_1(t) - \frac{\dot{x}_4(t)}{2\sqrt{x_4}} + \frac{1}{T_1} \psi_1 = 0. \]

(6)

Substituting now the first equation of system (3) into (6), we find the basic equation for the synthesis of the control law:

\[ (bu - \alpha x_1)\sqrt{\beta_\rho} = \frac{\dot{x}_4(t)}{2\sqrt{x_4}} + \frac{1}{T_1} \psi_1, \]

(7)

which reflects the effect of the electromagnetic part on the behavior of the EHVO.

Equation (5) is asymptotically stable with respect to the invariant manifold from \( \psi_1 \) (4); therefore, after the end of the transient processes determined by the quantity \( T_1 \), we will have:

\[ x_4 = \beta_\rho x_1^2. \]

(8)

Let us now introduce the second macro variable, which reflects the behavior of the mechanical part EGVO, i.e.:

\[ \psi_2 = y + k z + \lambda x_2, \]

(9)

or, taking into account (2) and (8), we have:

\[ \psi_2 = \gamma x_3 + x_4 + \lambda x_2 + k z - mg. \]

(10)

Then, substituting \( \psi_2 \) (10) into the second invariant relation:

\[ T_2 \psi_2(t) + \psi_2 = 0, \]

(11)

we get the equation:

\[ k y + \gamma x_3 + \dot{x}_4(t) + \lambda \dot{x}_2(t) + \frac{1}{T_2} \psi_2 = 0. \]

(12)

From (12), taking into account the second and third equations of system (3), we find the derivative of the additional variable:
\[ \dot{x}_4(t) = -\gamma x_2 + \lambda \left( \alpha_1 x_2 + \alpha_3 x_3 + \frac{x_4}{M} + z \right) - k_1 y - \frac{1}{T_2} \psi_2. \]  

(13)

Now, substituting the expression \( \dot{x}_4(t) \) from (13) into (7), we find the following control law EHVO:

\[
bu = a x_1 - \frac{1}{2} \sqrt{\beta_p x_4} \left[ \gamma x_2 - \lambda \left( \alpha_1 x_2 + \alpha_3 x_3 + \frac{x_4}{M} + z \right) - k_1 y - \frac{y + k_1 z + \lambda x_2}{T_2} \right] - \frac{\sqrt{\beta_p x_1} - \sqrt{x_4}}{\sqrt{\beta_p T_1}}.
\]

(14)

The control law (14) is the effect of the electromagnetic subsystem on the mechanical subsystem of the EHVO. Depending on the choice of parameters \( \beta_0, \beta_p, \lambda, T_1, T_2 \) we can get different properties of EHVO.

As noted above, the purpose of control is to fulfill the condition \( y \leq \varepsilon \) in formula (2). Depending on the design parameters of the EHVO with the control law \( u \) defined by expression (14), it is possible to obtain different values of the variable \( y \) and the coordinates of the position of the movable platform \( x_3 \) [4]. It should be noted that expression (14) for the control law \( u \) includes an integral component \( z = \int y dt \), which is designed to suppress external disturbances at the EHVO.

Comparative results for linear and nonlinear control laws are carried out for a specific EHVO, designed and parametrically modeled in three-dimensional space using the T-FLEX CAD computer-aided design system [1].

The software part and calculations were carried out using the ME’scopeVES Visual Engineering Series package, which is designed to solve problems of analyzing problems in the field of vibration and noise of mechanisms and structures using both experimental and analytical data [5].

5. Conclusions and simulation results

Figures 5-10 show the results of modeling EHVO with the control law \( u \) (14) and parameters \( a=33.3, b=5, \gamma=585000 \text{ kg/s}^2, m=10 \text{ kg}, M=100 \text{ kg}, \alpha_1 = 6.6 \text{ s}^{-1}, \alpha_2 = 5890 \text{ s}^{-2}, \beta_p = 10, \beta_M = 1, \lambda = 1, k = 1. \)
As can be seen from the results of modeling EGVO (1-14), the synthesized nonlinear control law $u$, determined by expression (14), provides an effective effect of external disturbances.

When comparing the properties of an EHVO with a linear control law, synthesized by a linear model in [7-10], with the properties of an EHVO with a nonlinear control law (14), it can be seen that the amplitude of fluctuations of the value $y$ (2) in an EHVO can reach the value and in an EGVO with a nonlinear control law (14), no more. Consequently, the main goal of constructing an optimal electromagnetic vibration-isolating support, consisting in minimizing the variable $y$, has been fulfilled.

So, in this work, it was obtained that the synthesized nonlinear control law of the EGVO (1) provides properties in relation to the suppression of various high disturbances. The developed method of a sequential system of nonlinear control systems can be applied to other designs and classes of vibration isolation devices used in various fields of modern technology.

References

[1] Glushkov S P, Fomichev P A and Fomicheva E V 2005 Vibration insulating hydraulic supports of a new generation. Novo-Siberian (in Russian)

[2] Zasyadko A A 2007 Electrohydraulic vibration protection systems. Modern technologies. System analysis. Modeling (Irkutsk: Publisher “Ir-GUPS”) Out. 2 (14) pp 16-24 (in Russian)

[3] Ion A V 2000 Means of reducing vibration and noise on ships (St. Petersburg: Publishing House of the Central Research Institute named after Academy A.N. Krylova) (in Russian).
[4] Fomichev P A, Fomicheva E V and Glushkov S P 2006 Electromagnetic hydraulic vibration isolating support: pat. 2262623 Ros. Federation, No. 2004106223/11, stated. 02.03.2004, publ. 20.10.2006, Bull No. 29 (in Russian).

[5] Fomichev P A and Fomicheva E V 2020 Perspective directions of modern vibroinsulation based on nanocomposite materials with hierarchic structure. Proceedings of the international conference on physical mesomechanics. Materials with multilevel hierarchic structure and intelligent manufacturing technology (Tomsk: 5–9 Oct. 2020) vol 2310 Art. 020099.

[6] Fomichev P A and Fomicheva E V 2019 IOP Conference Series: Earth and Environmental Science 2019 (022102).

[7] Gutner I E, Nikiforov V O, Sergachev I V 2003 Mathematical model of a vibro-insulated support with an electromag-thread active element Mechatronics, automation and control 1 13-18 (in Russian)

[8] Kolesnikov A A 2006 Synergetic methods of managing complex systems: the theory of system synthesis (Moscow: Publisher “ComBook”) p 240 (in Russian)

[9] Eliseev S V and Zasyadko A A 2004 Modern technologies. System analysis. Modeling (Irkutsk: IrGUPS) No. 1 pp 26-34 (in Russian)

[10] Wakasugi T, Watanabe T and Seto K 2004 Vibration and Motion Control using Two-degree-of-freedom control system for a Three-Dimensional Flexible shaking Table. In: Proc. of 7th Int. Conf. on Motion and Vibration control No. 132 Tokio.