Estimation of Dynamic Characteristics of Vibration Protection Systems of a New Type for Water Transport Vessels

P A Fomichev¹, E V Fomicheva¹

¹Novosibirsk State Technical University, Novosibirsk, 630132, Russian Federation

E-mail: lena054@mail.ru, fomicheva.elena.70@mail.ru

Abstract. The use of traditional means of vibration isolation of ship power plants does not always give the desired effect, which predetermines the need to search for and use fundamentally new devices to improve the efficiency of vibration isolation of a ship engine. This can be achieved by installing active-passive vibration isolators in the elastic mounts of the engine, such as electromagnetic hydraulic vibration isolators (EHVO) for auxiliary engines and other marine equipment. 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. The known functions of time obtained by solving the equations were used to calculate the dynamic parameters of the EHVO: vibration energy, periodicity, overheating of the coils and efficiency.

1. Introduction

The development of modern ship power plants is associated, on the one hand, with an increase in the power and speed of mechanisms, which in many cases are sources of intense noise and vibrations, on the other hand, with an increasing scale of use of precision instruments and equipment for various purposes, sensitive to vibrations. Currently, the design methods themselves provide for the solution of problems to significantly reduce vibration already at the stage of the technical assignment due to the special arrangement of the premises relative to the sources of vibration and noise, the rational choice of the design of the body itself, the thickness of the sheathing sheets, the use of various, most progressive vibration-insulating materials and devices [1]. Unfortunately, not all shipboard equipment can be effectively isolated from the ship's hull for a number of reasons. So, for example, the main motor must be connected to the housing to transmit operating forces and, at the same time, not connected to it for isolation from vibration. Moreover, this contradiction is so deep that it is impossible to resolve it by a compromise on the basis of linear vibration damping elements. Vibration isolators with special properties are required to maintain the position of the engine relative to the housing and at the same time not transmit vibration to the housing. However use of traditional vibroinsulators often doesn't solve a vibration insulation problem. It is obviously possible to resolve this problem, using the newest systems of vibration insulation [2].
2. Problem statement and its solution

Works [3-5] give a detailed description and a schematic drawing of the EHVO. It is clear that the electromagnetic actuator of the vibration-isolating support is an electromechanical device, one of the defining units of which are electromagnets that perform mechanical work to set the hydraulic piston in motion, or hold it motionless, or perform both sequentially. Despite the seeming simplicity of the design and principle of operation, the calculation of the 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.

For the successful design and optimization of the EHVO parameters, we will calculate the dynamic parameters of the electromagnetic component of the electromagnetic hydraulic vibration-insulating support.

Using the known functions of time B (t), h (t), obtained by solving the equations, we calculate the dynamic parameters of the EHVO: vibration energy, frequency, overheating of the coils, efficiency.

The energy of the piston stroke can be calculated by the formula:

$$ A = \frac{m_{\text{f}} v^2}{2} $$  \hspace{1cm} (1)

where V - the piston speed at the end of the working stroke.

In relative terms, we get

$$ A = \frac{\pi r_a^3 B_{\text{f}}}{{\mu_0} 2} \cdot I_{\text{II}} v^2 $$  \hspace{1cm} (2)

Cycles per minute $n = \frac{60}{t_{\text{II}} T}$

The superheat temperature is calculated using the heat balance equation for EHVO:

$$ I^2 R = K_T \tau S_{\text{II}} $$  \hspace{1cm} (3)

where: $S_{\text{II}}$ - surface, winding cooling; $K_T$ - coefficient of heat transfer from the winding cooling surface; $\tau$ - overheating temperature; $I = \sqrt{\frac{1}{T_a} \int_0^{T_a} I^2 dt}$; $T_a$ - the absolute time of the movement cycle;

$i_a$ - the absolute value of the instantaneous current: $i_a = \frac{B_{\text{II}} n_a}{\mu_0 W} \cdot I \cdot f(t)$ where the specific magnetizing force $f(t)$ is calculated from the known function B (t).

The cooling surface during natural cooling for an electromagnet is determined by the formula: $S_{\text{II}} = 2\pi r_{2a} I_k^2 + \alpha \cdot 2\pi r_{a} I_k^2 = 2\pi r_{a}^2 I_k (r + \alpha)$, where: $r_{2a}$ - outer radius of the winding; $\alpha$ - an experimental coefficient that takes into account the conditions of heat transfer [6].

With artificial cooling, $S_{\text{II}}$ depends on the design of the cooling system, i.e. on the number of sections of the winding, the number and layout of the channels [7].

For electromagnets EHVO, you can use the axial scheme [8], then

$$ S_{\text{II}} = I_\text{a} \cdot 2\left(2\pi r_{Ia} + 2\pi r_{Ila} + \ldots + 2\pi r_{qa}\right) = 4\pi r_\text{a}^2 I \cdot \sum_i r_i $$  \hspace{1cm} (4)

where: $r_{Ia}, r_{Ila}, \ldots, r_{qa}$ - the average radii of the channels; $q$ is the number of channels; $i$ - channel number.

From equation (3) we obtain $\tau$ in relative terms:
\[ \tau = \frac{0.25B_{II}^{2}\rho(r+1)}{\mu_{0}n_{a}K_{r}K_{3}T(r-1)} \int_{0}^{T} f_{1}^{2} dt \]  

(4)

where \( K_{r} \) is the coefficient determined by the cooling conditions.

With free cooling \( K_{r} = K_{T}(r + \alpha) \), under artificial \( K_{r} = 2K_{T} \sum_{i} \), where \( K_{T} \) is determined according to [8].

For EHVO, overheating of the coils of both electromagnets is assumed to be the same, then the heat balance equation has the form

\[ I_{1}^{2}R_{1} + I_{2}^{2}R_{2} = K_{T} \tau S_{II} \]  

(5)

where \( I_{1} = \sqrt{\frac{1}{T_{a1}} \int_{0}^{T} i_{a1}^{2} dt} \) , \( I_{2} = \sqrt{\frac{1}{T_{a2}} \int_{0}^{T} i_{a2}^{2} dt} \) - instantaneous values of the coil currents, determined using the functions \( B_{1}(t), B_{2}(t) \); \( S_{II} \) - total cooling surface.

After transformations (5) we get in relative values:

\[ \tau = \frac{0.25B_{II}^{2}\rho(r+1)}{\mu_{0}n_{a}K_{r}K_{3}T(r-1)} \int_{0}^{T} (f_{1}^{2} + K_{T}f_{2}^{2}) dt \]  

(6)

Coefficient of performance (COP): \( \eta = \frac{A}{W_{C}} \). In relative values for EHVO, we obtain

\[ \eta = \frac{1.57n_{a}B_{II}^{2}l_{II}V^{2}}{E'\sqrt{\mu_{0}y} \int_{0}^{T} (f_{1} + K_{T}f_{2}) dt} \]  

(7)

For a successful solution to the problem of cooling an EHVO, it is necessary to analyze the factors affecting its heating and heat transfer [9]. Cooling of the support is provided when the conditions [10] are met: 1) all the heat released in the support is given to the environment; 2) the maximum winding temperature does not exceed the set one.

Heat removal from a heated surface is described by the well-known empirical formula

\[ Q = \alpha F(v_{C} - v_{I}) \]  

(8)

where: \( Q \) is the amount of heat removed; \( \alpha \) - heat transfer coefficient (CTO); \( F \) - cooling surface; \( v_{C} - v_{I} = \Delta v_{C} \) - the temperature difference between the cooling surface and the cooling medium (temperature head).

The maximum winding temperature can be represented by the expression

\[ v_{m} = \theta_{m} + \sum_{0}^{i} \Delta v_{I} \]  

(9)

where: \( \theta_{m} \) - the maximum temperature difference in the winding; \( \sum_{0}^{i} \Delta v_{I} \) - total temperature drop on the way of heat flow to the cooling surface.

Equations (8) and (9) combine all the factors influencing the thermal regime of the EHVO. Let's take a closer look at these factors.
The heat transfer coefficient (CTO) is a complex function of a large number of parameters that determine the heat transfer process. With natural cooling, the CTO depends mainly on the thermophysical properties of the cooling medium and the temperature head, with an increase in which it grows. In the case of forced cooling, the CTO is determined by the speed of movement of the cooling medium and can vary over a very wide range: from $10 \text{ Bm} / \text{m}^2 \cdot ^\circ \text{C}$ with natural air cooling to $50,000 \text{ Bm} / \text{m}^2 \cdot ^\circ \text{C}$ with boiling liquids. A wide range of changes provides the ability to select the appropriate method and cooling system.

It is important to note that the amount of removed power cannot be increased in proportion to the increase in CTO $\theta_m$. This is due to the condition that the maximum temperature should not exceed the specified values. With an increase in CTO, with an increase in the power dissipated, the temperature drop in the winding $\theta$ and the total temperature drop $\sum_0^i \Delta \nu_i$ proportionally increase.

The limiting amount of heat removed from the winding is ultimately determined only by the temperature difference in it. Under ideal cooling conditions ($F \rightarrow \infty$, $\Delta v_C$ and $\sum_0^i \Delta \nu_i \rightarrow 0$) the temperature difference in the layer of a flat winding for a one-dimensional heat flux with symmetric cooling $\theta = v_m - v_i = \frac{q_m h^2}{8\lambda}$, whence the limiting value of specific losses $q_m = \frac{8\lambda (v_m - v_i)}{h^2}$, where: 

$\lambda$ - coefficient of thermal conductivity of the winding; $h$ - height (thickness) of the winding.

The difference between the temperature of the cooled surface and the temperature of the cooling medium $v_C - v_i$, the so-called temperature head $\Delta v_C$, enters into equations (8) and (9), which determine the thermal regime $\Delta v_C$, which determines the complex nature of the effect on the heating of the support. With an increase in the temperature difference, both the heat transfer coefficient and the power of the removed losses $Q$ increase, i.e. $\Delta v_C$ is a useful component of the maximum temperature. Providing increased heat removal from a unit surface, high values $\Delta v_C$ reduce the proportion of temperature differences in the winding $\theta$ and the total temperature drop $\sum_0^i \Delta \nu_i$, since the maximum temperature must remain unchanged.

In turn, since $\theta$ and $\sum_0^i \Delta \nu_i$ are proportional to the specific losses, an increase in the dissipated power under unchanged cooling conditions inevitably leads to an increase in the temperature drop in the winding and the total temperature drop. One of the main tasks of thermal calculation is to find rational relationships between the temperature head and the temperature difference in the winding, which would provide cooling of the support with the simplest possible methods and design schemes.

The maximum temperature difference in the winding is proportional to the square of the winding height and the intensity of internal heat sources and depends on the direction and value of heat fluxes, i.e. cooling conditions. So, if for a flat winding with one-dimensional heat flux and double-sided cooling $\theta_m = \frac{q h^2}{8\lambda}$, then with one-sided heat removal $\theta_m = \frac{q h^2}{2\lambda}$.

From the last equations, possible ways to reduce the maximum temperature drop $\theta_m$ are visible (decrease in specific losses, winding height $h$, increase in thermal conductivity and ensure symmetric cooling conditions on both sides). A decrease in specific losses $q$ is achieved by increasing the support efficiency.

The temperature of the winding of any electrical machine as a system with internal heat sources is directly proportional to the intensity of volumetric heat release or specific power losses per unit
volume. In an electromagnetic hydraulic vibration isolating support, specific losses depend on the efficiency and current density. The dependence of the loss power $Q$ on the efficiency is expressed by the well-known equation $Q = P \frac{1-\eta}{\eta}$, where $P = \frac{A \cdot n}{60}$ is the useful power [1].

The hyperbolic nature of this dependence (Fig. 1), presented in the form of a graph $Q/P = f(\eta)$, leads to a sharp increase in losses with a decrease in efficiency. If in the efficiency zone of rotating machines the share $Q/P$ of losses is $0.1 \div 0.5$, then for EHVO it is 5 - 7 times higher. It can be seen from the graph that an increase in efficiency from 0.4 to 0.5 leads to a decrease in losses by one and a half times.

![Figure 1. Change in the ratio of power losses to useful power depending on efficiency (1 - EHVO; 2 - rotating machines).](image)

A feature of the EHVO design is the location of the most thermally vulnerable element (winding) in the most heat-stressed place. The winding, inside which the piston rod moves, is enclosed in a magnetic circuit (yoke and pole). In the piston rod and the magnetic circuit, losses from hysteresis and eddy currents take place. The heat flux from the winding goes mainly in the radial direction, overcoming the thermal resistance of the wall with internal heat sources.

Significant specific losses concentrated in the winding create a high heat flux density, which leads to large temperature drops inside the support and an increase in the temperature level of the winding.

Considering the noted features, we come to the need to intensify the heat transfer processes in the EHVO, in connection with which the issues of choosing and calculating cooling systems become on a par with the main issues of calculating and designing supports.

### 3. Conclusions

- 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.
- Based on the known functions of time, obtained by solving the equations, the dynamic parameters of the EHVO were calculated: vibration energy, periodicity, overheating of the coils and efficiency.
The use of EGVO is most expedient for vibration protection of auxiliary ship engines and other ship equipment (having a small mass).

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