Approach Heating Processes in Multiphase Gas-Hydraulic Damper

A Ermolaev\textsuperscript{1,a}, S Okhulkov\textsuperscript{2,b}, A Plehov\textsuperscript{1} and D Titov\textsuperscript{1,c}

\textsuperscript{1}Nizhny Novgorod State Technical University n.a. R.E. Alekseev, 603950, Minin St., 24, Nizhny Novgorod, Russia
\textsuperscript{2}Mechanical Engineering Research Institute of RAS, 603024, Belinsky St., 85, Nizhny Novgorod, Russia

E-mail: \textsuperscript{a}acidwolfvx@rambler.ru (corresponding author), \textsuperscript{b}oxulkovs@mail.ru, \textsuperscript{c}d.titov@nntu.ru

Abstract. The article proposes a mathematical model of temperature control of a multi-phase gas-hydraulic vibration isolator due to application of gas-regulated heat pipe. During the operation of the vibration isolator with magnetorheological transformers, mechanical energy is absorbed, which is converted into heat. The use of a gas-controlled heat pipe ensures the removal of heat from the object, the creation of an isothermal zone inside it and the temperature stabilization of the object. This ensures the preservation of the working properties of the magnetorheological fluid, in particular, its viscosity, and practically stabilizes the parameters of the amplitude-frequency characteristic of the vibration-insulator, regardless of the time of continuous operation and the ambient temperature. The article presents experimental methods for determining the thermal coefficient and rate of heating of a vibration-isolator, which allows making reasonable design decisions in the design of vibration protection systems.

1. Introduction

A great variety of electric drives in modern production plants brings about conditions for synchronization on one or several frequencies that leads to transition processes time increment in energy-intensive equipment [1, 2]. Transition processes time increment leads to increase in energy consumption and additional growth of harmful vibrations and hazardous low-frequency wobbles. These processes shorten power-units life and result in engineering constructions failure. Consequently, vibration levels decrease in energy-intensive equipment stationary and transient operation modes has always been an acute task [3].

Nowadays vibration isolators (Fig. 1) represent the major trend of machines and power-units vibration protection. Vibration isolators comprising magnetorheological transformers with magnetorheological fluids controlled by electromagnetic fields are placed between vibro-active and vibro-isolated objects [4, 5].
Fig. 1 shows an electric machine (EM) connected to a working machine (WM). Both the machines are placed on the common platform connected with the foundation through a vibration isolator (VI).

While the vibration isolator and magnetorheological transformers are in operation, mechanical energy is absorbed and converted into heat. This leads to magnetorheological fluid heating and as a result reduction in the vibration isolator operational efficiency [6-8].

A mathematical model of vibration isolator heating processes is suggested in the article. It is based on determining active mechanical power as well as the cooling process due to gas-controllable heat pipe.

Gas-controllable heat pipe provides the object heat removal and temperature stabilization creating isothermal region inside it. Thermostatic effect is achieved by the fact that such pipe conductivity to a large extent depends on the vaporizer temperature [9, 10]. Such heat pipe normally comprises an ordinary heat pipe and an inert noncondensable gas reservoir connected to it. The reservoir sustains permanent vapor pressure in different operation modes.

2. Determining Mechanical Power Flow by Multiphase Gas-Hydraulic Vibration Isolator
Fig. 2 shows multiphase vibration isolator. Fig. 2 shows 1 – rubber rim; 2 – magnetorheological fluid; 3 – body; 4 – magnetic core; 5 – electromagnet coil; 6 – multiphase system gas phase; 7 – heat conducting damping plate; 8 – multiphase system liquid phase. 6 and 8 represent a gas-controllable heat pipe.
A multiphase vibration isolator can be regarded as a vibration insulation system with one degree of freedom (Fig. 2).

Fig. 3 shows a vibration isolator model as a part of vibration insulation system in the form of lumped mass $m$ on the rubber rim – an elastic member its other part rigidly fixed to the foundation. In this system members of elasticity, mass and friction are separated from each other.

![Figure 3](image)

**Figure 3.** Physical model of single-mass vibration insulation system with one degree of freedom in Z coordinate; $m$ mass concentrated in the gravity center.

Oscillatory $m$ –mass body motion equation is written as:

$$m\ddot{z} + b\dot{z} + cz = F,$$

where $m$ – mass; $b$ – viscous friction coefficient; $c$ – rigidity; $F$– external force, changing according to sinusoidal law; $z$, $\dot{z}$, $\ddot{z}$ – vibration displacement, vibration speed and vibration acceleration respectively.

Vibration active power depends on viscous friction values and it determines power losses (dissipation) in the system. Reactive power is proportional to the difference between potential and kinetic energy [11, 12].

Let us determine active and reactive system power at sinusoidal external influence.

The system displacement is determined as:

$$\frac{z}{F} = \frac{1}{m} \left[ \omega_n^2 - \omega^2 + i2\zeta\omega\omega_n \right],$$

where $\omega$ – disturbing frequency, $\omega_n$ – natural frequency, $\zeta$ – damping coefficient.

Natural oscillation frequency is determined as:

$$\omega_n = \sqrt{\frac{c}{m}}.$$  

Damping coefficient:

$$\zeta = \frac{b\omega_n}{2m}.$$  

Let us further determine:

$$\dot{z} = \frac{F \Omega}{m\omega_n^2 \left[ 1 - \Omega^2 + 2\zeta\Omega \right]}.$$

where $\Omega = \omega/\omega_n$– frequencies ratio.
Vibration power is determined as:

\[
S_p = \frac{F^2}{2m\omega_n} \left[ \frac{2 \zeta \Omega^2}{(1 - \Omega^2)^2 + (2 \zeta \Omega)^2} \right] + i \frac{\Omega (1 - \Omega^2)}{(1 - \Omega^2)^2 + (2 \zeta \Omega)^2}.
\] (4)

Active power can be expressed from (4):

\[
P_f = \frac{F^2}{2m\omega_n} \left[ \frac{2 \zeta \Omega^2}{(1 - \Omega^2)^2 + (2 \zeta \Omega)^2} \right]
\]

and reactive power:

\[
Q_f = \frac{F^2}{2m\omega_n} \left[ \frac{\Omega (1 - \Omega^2)}{(1 - \Omega^2)^2 + (2 \zeta \Omega)^2} \right].
\]

3. Mathematical Heating Model Regardless of Vibration Isolator Thermostatic Effect

The amount of heat generated in vibration isolator during \( dt \) period will be:

\[
dQ = P_f \cdot dt.
\]

A part of this heat is consumed by vibration isolator warming and its temperature rise, the rest of the heat being withdrawn from the vibration isolator surface by heat output and gas-controllable heat pipe temperature control.

Vibration isolator warming energy equals

\[
dQ_1 = G \cdot c_t \cdot d\Theta,
\]

where \( G \)- vibration isolator mass, kg; \( c_t \)- specific heat capacity of the vibration isolator material, \( J/(kg \cdot K) \); \( \Theta = \nu - \nu_0 \)- the vibration isolator over-temperature \( \nu \) relative to ambient temperature \( \nu_0 \).

Energy withdrawn from the vibration isolator surface during \( dt \) period due to heat output is proportional to the vibration isolator over-temperature relative to ambient temperature:

\[
dQ_2 = \lambda \cdot S \cdot \Theta \cdot dt,
\]

where \( \lambda \)- heat output overall coefficient equal to heat transfer by convection and radiation coefficients sum, W/m\(^2\)-K; \( S \)- the vibration isolator cooling surface, m\(^2\).

Heat balance equation can be written as:

\[
dQ = dQ_1 + dQ_2
\]

or

\[
\frac{P_f}{Gc_t} = \frac{d\Theta}{dt} + \frac{\lambda S}{Gc_t} \Theta.
\]

The solution of this differential equation will be vibration isolator heating dependence on time period (at the initial time the vibration isolator has ambient temperature):
\[ \Theta = \frac{P_f}{\lambda \cdot S} \left( 1 - e^{-\frac{\lambda \cdot S}{G \cdot c_v}} \right). \] (5)

### 4. Mathematical Heating Model with Vibration Isolator Thermostatic Effect

Thermostation process special feature is that when the heating starts affected by heat source, the heat pipe is idle. With the temperature rise the vapor flow ousts the gas in the heat removal region the vapor at this moment reaching the condensing region. The heat pipe conductivity drastically increases and the pipe starts cooling the object at an intensive rate.

Such tasks can be solved by approximate methods described in [13]. Determining the body heating rate holds a central position in these tasks solution. At this, formula (5) is transformed and acquires the following form:

\[ \Theta = kP \left( 1 - e^{-r \cdot r_{\text{e}}} \right), \] (6)

where \( k \) – heat coefficient determined experimentally; \( P \) – the heat source power; \( r \) – heating rate.

The experimental method of determining heat coefficient \( k \) is the following. Power value \( P \) is measured and the following dependency is determined experimentally:

\[ t_s - t_i = kP, \] (7)

where \( t_s \) - ambient temperature; \( t_i \) - the body stationary temperature during the heating process.

At the first stage the vibration isolator heating rate \( r' \), cooled by the gas-controllable heat pipe can be determined as [14]:

\[ r' = \frac{r_0}{2} \left( n - \sqrt{n^2 - 4kb} \right), \]

where \( n = 1 + b + kb \); \( b = \frac{C_0}{\varphi_0 \cdot C_2} \); \( k = \alpha S_2 / \sigma_1 \); \( r_0 = \sigma_1 \varphi_0 / C_0 \); \( C_0 \) – the thermostation object heating capacity (magnetorheological fluid); \( C_2 \) – the body and the heat pipe adjacent to it heating capacity; \( \alpha \) – heat transfer effective coefficient; \( \sigma_1 \) – plate conductivity \( \sigma_1 \) (Fig. 2), depending on the material and geometrical dimensions; \( S_2 \) – the condensing region outside area; \( \varphi_0 \) – non-dimensional parameter, characterizing the object temperature field non-uniformity degree which can be calculated according to the formula:

\[ \varphi_0 = \left( \sqrt{H^2 + 1.44H + 1} \right)^{-1}, \]

where \( H = \sigma_{03} K_0 / \left( \lambda V_0 \right) \); \( \sigma_{03} = \sigma_1 \alpha S_2 / (\sigma_1 + \alpha S_2) \); \( V_0 \) and \( K_0 \) – the object volume and shape coefficient.

For cylindrical bodies the shape coefficient can be calculated as follows:

\[ K_0 = \frac{1}{\left( \frac{2.405}{r_0} \right)^2 + \left( \frac{\pi}{l_0} \right)^2}, \]

where \( l_0 \) cyliner height; \( r_0 \) – cylinder radius.

At the second stage, when the heat pipe cools the object, the heating rate will be:

\[ r'' = \sigma_0 \varphi_0 / C_0, \]
where \( \varphi_0 = \left( \sqrt{H_1^2 + 1.44H_0^2} + 1 \right)^{-1} \); \( H_0 = \sigma_iK_0f(\lambda_0V_0) \); \( \lambda_0 \) – thermostation object heat conductivity.

5. Conclusion
The use of the effect of thermal stabilization on the basis of a gas-regulated heat pipe makes it possible to change the heating rate of the vibration isolator. This ensures the preservation of the working properties of the magnetorheological fluid, in particular, its viscosity, and practically stabilizes the parameters of the amplitude-frequency characteristic of the vibration-insulator, regardless of the time of continuous operation and the ambient temperature.

The article presents experimental methods for determining the thermal coefficient and rate of heating of a vibration isolator, which allows to reasonably making design decisions when designing vibration protection systems.

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