Dependence of Hydraulic Fluid Added Mass in Hydromounts Throttle Channels on Controlling Magnetic Field

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Abstract. The method of finding added mass of hydraulic magnetorheological fluid (MRF) in choking channels of magnetorheological transformer (MRT) of hydraulic vibration mount (hydromount) considering controlling magnetic field is presented in the article. Calculation of MRF added mass of Fluid MRF\textsubscript{132DG} mark developed by LORD (USA) is given, filling the hydromount with MRT designed for damping impact loads. Hydromount with MRT has two controlled inductive slit choking channels in which MRF is excited by external magnetic field. MRF added mass unaffected by magnetic field was considered in this article.

1. Introduction

Hydromount with MRT structure is connected to inertia member conversion of motion – magnetorheological fluid mass in MRT choking channels [1,2]. MRF of MRF\textsubscript{132DG} mark has been chosen as the hydromount hydraulic fluid [3].

Vibration insulation can be carried out by tuning hydromounts to frequencies corresponding to hydromount dynamic rigidity minimal values [4,5]. This is reached in hydromounts by changing hydraulic damping due to fluctuating fluid inertia forces in its working chambers and the hydraulic fluid rate of flow in choking channels [6,7].

2. Hydromount MRT for Damping Impact Loads

In hydromounts with MRT, designed for damping impact loads in controlled choking channels, MRF is affected by magnetic field of filed magnets (FM) [8,9,10]. When throttling MRF from the hydromount working chamber into its compensating chamber through MRT choking channels, viscous friction of MRF layers appears [11,12]. At this, thermal energy is released and the operation is performed [13-15].

Fig. 1 shows a two-channel MRT diagram, controlled hydromount for damping impact loads with two choking channels and one field magnet.

MRF added mass in MRT choking channels depends on the controlling magnetic field change, thus when calculating hydromounts with MRT damping characteristics it is necessary to take into consideration the controlling magnetic field action.
It is found that the MRF reduced mass in choking channels regardless of the controlling magnetic field action can a hundredfold or a thousand-fold exceed the actual mass of hydraulic MRF in choking channels [1, 2]. Besides, an acute task of investigating the MRF added mass change under a magnetic field appears which will allow to build choking channels in the hydromount MRT in the optimal way.

Figure 1. MRT diagram, hydromount controlled by magnetic field for damping impact loads with two choking channels and FM.

3. Calculation of MRF Added Mass in MRT Choking Channels Considering the Controlling Magnetic Field Action

The term added mass of hydraulic MRF in MRT hydromount choking channels is simplification of term inertia increase by relative motion [1]. Regardless of the controlling magnetic field action, hydromount-to-operating-frequency tuning is carried out by creating inertia along the hydromount rim relative motion. At this relative rim motion is provided by radii squares ratio of the rim piston action $R_{rim}$ and the equivalent choking channel $R_{c.h}$ [1].

MRT added mass $m_{MRT}$ due to MRF added mass, exceeding MRF actual mass in hydromount choking channels unaffected by external magnetic field is possible to calculate by empirical expression [4, 6]

$$m_{MRT}^{(H \neq 0, f)} = m_{IT} = \frac{\pi R_{rim}^2 m_f^{(H \neq 0, f)}}{\pi R_{c.h}^2}, \quad m_f^{(H \neq 0, f)} = \rho_f^{(H \neq 0, f)} \ell \pi R_{c.h}^2,$$

where $m_{MRT} = m_{IT}$ – MRT added mass, equal to MRF added mass in $m_{IT}$ inertia transformer unaffected by external magnetic field; $m_f – MRF$ mass in choking channel of length $\ell$ [m]; $\rho_f = 2950$ kg/m$^3$ – MRF density.

The unaffected by magnetic field hydromount tuning frequency equals [1]

$$f_{set} = \left(\frac{1}{2\pi}\right) \sqrt{C_{rim}/m_{MRT}} = \left(\frac{1}{2\pi}\right) \sqrt{C_{rim}/m_{IT}},$$

where $C_{rim}$ – static stiffness of the hydromount rubber rim.

MRF added mass is calculated for a single hydromount choking channel. The choking channel inner cross-sectional area is selected as a constant and it is equal to
\[ \pi \cdot R^2_{\text{ch}} = 2.801 \cdot 10^{-3} \, m. \]

Length (height) of poles of FM MRT magnetic core is \( \ell = 15 \, \text{mm} \), therefore length of medium rectangular stretches of MRT choking channel is also selected equal to \( \ell = 15 \, \text{mm} \).

MRF MRF-132DG [8] actual mass at the rectangular choking channel stretch of length \( \ell = 15 \, \text{mm} \) within the FM poles area without magnetic field at the temperature of 20ºC is equal to

\[ m_f^{(H=0,20^\circ\mathrm{C})} = \rho_f^{(H=0,20^\circ\mathrm{C})} \ell \pi R^2_{\text{ch}} = 1,0906 \cdot 10^{-3} \, \text{kg}. \]  

(3)

In a choking channel under the magnetic field MRF added mass is found by theoretical and field research.

To calculate MRF added mass in a choking channel, being part of expression (1) it is necessary to make a modification considering the external magnetic field force action, such modification being magnetic field strength.

Intensity vector \( H \) coincides with force vector direction \( F \).

\[ H = F / m_0, \]  

(4)

where \( F \) - mechanical force affecting test magnet unit mass \( m_0 \).

Applying the magnetic field strength notion through the mechanical force and substituting in formula (4) test magnet unit mass \( m_0 \) for MRF mass, a formula for mechanical force \( F \) is obtained, affecting the MRF flux in a choking channel

\[ F = H m_{\text{MRT}}. \]  

(5)

The mechanical force affecting MRF flux can be presented through the reduced mass \( m_{\text{red}} \)

\[ m_{\text{red}}g = H m_{\text{MRT}}, \]  

(6)

where \( g \) – free-fall acceleration.

Thereafter, MRF \( m_{\text{red}} \) added mass, which is added to external load inertia mass at relative motion is expressed as

\[ m_{\text{red}} = H m_f / g. \]  

(7)

At numerical estimate of hydromounts with MRT damping characteristics and at their hydraulic MRF temperature increase it is also necessary to take into account dependence of dynamic viscosity on heating temperature. For MRF by LORD MRF-132DG corporation viscosity value at 20º C is 0,93±0,020 Pa∙s [7]. In article [7] a formula is suggested connecting MRF viscosity change depending on the temperature

\[ \eta_T = \eta_{20} \cdot \left[ 1 - C_T \cdot \left( \frac{T - 293,15}{293,15} \right) \right]. \]  

(8)

where \( \eta_{20} \) – MRF dynamic viscosity at 293 K, \( C_T \) – temperature coefficient (for MR Fluid MRF-132DG \( C_T = 1,9 \)), \( T \) K – MRF temperature.

Expression (3) for MRF added mass considering (7) can be written as follows:

\[ m_{\text{red}}^{(H=0,20^\circ\mathrm{C})} = \rho_f^{(H=0,20^\circ\mathrm{C})} \ell \pi R^2_{\text{ch}} \frac{H}{g}, \]  

(9)

and it shows that MRF added mass is proportional to the equivalent choking channel area and the magnetic field strength.

Hydraulic MRF added mass \( m_f \) in MRT choking channel under the magnetic field and temperature is determined by [3, 4]
\[ m_{\text{MRT}} = \frac{n_{i,j}(t)}{\lambda_{1,1}(20^\circ)} \cdot \ell \cdot \pi \cdot R_{\text{ch}}^2 \cdot \frac{H}{g} \]  

where \( \rho_f = \eta_{i,j}(t) / \lambda_{i,j}(20^\circ) \) – hydraulic MRF density; \( \eta_{i,j}(t) \) – dynamic viscosity of \( j \) – temperature MRF; \( \lambda_{1,1}(20^\circ) \) – kinematic viscosity at 20 °C and at minimal magnetic field strength \( H = 9 \text{ kA/m} \) (see table 1).

When calculating MRF added mass under the temperature and the controlling magnetic field, data of table 1 are used.

At MRF single-phasing heating in its density is constant

\[ \rho_f = \eta_{i,j}(t) / \lambda_{1,1}(20^\circ) = \eta_{i,j}(20^\circ) / \lambda_{1,1}(20^\circ) = \cdots = \eta_{i,j}(60^\circ) / \lambda_{1,1}(60^\circ). \]  

MRF dynamic viscosity at \( j \)-temperature is determined considering the reference point arbitrary accepted at 20 °C:

\[ \eta_{i,j}(t) = \left( \lambda_{i,j}(t) / \lambda_{1,1}(20^\circ) \right) \cdot \eta_{i,j}(20^\circ) = \rho_f \lambda_{i,j}(t), \]  

where \( \lambda_{i,j}(t) / \lambda_{1,1}(20^\circ) \) – relative temperature coefficient of MRF viscosity.

Table 1. Values of hydraulic MRF viscosity of MR-fluid MRF-132DG depending on the temperature and the magnetic field strength from 9 kA/m to 252 kA/m within the temperature range of 20 °C up to 60 °C.

| \( H \), kA/m | 9      | 39     | 67     | 89     | 128    | 152    | 179    | 219    | 252    |
|--------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| \( \eta_{11} \), mPa·S | 530    | 710    | 830    | 880    | 920    | 950    | 990    | 1015   | 1030   |
| \( \eta_{12} \), mPa·S | 682,7  | 757,5  | 794,9  | 822,9  | 860,4  | 888,4  | 925,8  | 949,2  | 963,2  |
| \( \eta_{13} \), mPa·S | 635,4  | 705,1  | 739,9  | 765,9  | 800,7  | 826,9  | 861,7  | 883,4  | 896,5  |
| \( \eta_{14} \), mPa·S | 588,1  | 652,5  | 684,7  | 708,9  | 741,1  | 765,3  | 797,5  | 817,6  | 829,7  |
| \( \eta_{15} \), mPa·S | 635,4  | 705,1  | 739,9  | 765,9  | 800,7  | 826,9  | 861,7  | 883,4  | 896,5  |
| \( \eta_{16} \), mPa·S | 540,8  | 600,1  | 629,64 | 651,86 | 681,49 | 703,71 | 733,34 | 751,89 | 762,97 |

Relative temperature coefficient of MRF viscosity is presented as follows

\[ k_{ij}(t) = \lambda_{ij}(t) / \lambda_{1,1}(20^\circ) = \eta_{ij}(t) / \eta_{1,1}(20^\circ), k_{ij}(t) \neq k_{1,1}(20^\circ), k_{1,1}(20^\circ) = 1. \]  

Thereafter, MRF added mass considering relative temperature coefficient of MRF viscosity under the external magnetic field and temperature is determined through kinematic viscosity ratio

\[ m_{\text{MRT,ij}} = k_{ij}(t) \rho_f(H,0,t) \ell \pi R_{\text{ch}}^2 \frac{H}{g} = \frac{\lambda_{ij}(t)}{\lambda_{1,1}(20^\circ)} \rho_f(H,0,t) \ell \pi R_{\text{ch}}^2 \frac{H}{g}, \]  

or finally through dynamic viscosity ratio as

\[ m_{\text{MRT,ij}} = \frac{\eta_{ij}(t)}{\eta_{1,1}(20^\circ)} \rho_f(H,0,t) \ell \pi R_{\text{ch}}^2 \frac{H}{g}. \]  

MRF-132DG MRF added mass in a choking channel of length \( \ell = 15 \text{ mm} \) within the Hydro Mount (HM) – 95 FM poles area at the magnetic field strength 252 kA/m, temperature of 20°C and \( \rho_f = 2950 \text{ kg/m}^3 \) is equal to
Therefore, when designing hydromounts HM – 95 MRT with MRF MRF-132DG in a choking channel of length \( \ell = 15 \) mm within the FM poles area at the magnetic field strength and \( j \)-temperatures.

| \( H \), kA/m | 9  | 39 | 67 | 89 | 128 | 152 | 179 | 219 | 252 |
|---|---|---|---|---|---|---|---|---|---|
| \( m_{\text{supr}} \), [kg] | \( \eta_{H1} \) | \( \eta_{H2} \) | \( \eta_{H3} \) | \( \eta_{H4} \) | \( \eta_{H5} \) | \( \eta_{H6} \) | \( \eta_{H7} \) | \( \eta_{H8} \) | \( \eta_{H9} \) |
| \( m_{\text{supr1}} \) (20º) | 28,016 | 37,532 | 43,875 | 46,5187 | 48,6332 | 50,219 | 52,3335 | 53,6551 | 54,4448 |
| \( m_{\text{supr3}} \) (30º) | 26,198 | 35,095 | 41,031 | 43,5002 | 45,4826 | 46,9627 | 48,9398 | 50,1767 | 50,9168 |
| \( m_{\text{supr5}} \) (40º) | 24,385 | 32,663 | 38,187 | 40,4871 | 42,3267 | 43,7117 | 45,5513 | 46,6984 | 47,3909 |
| \( m_{\text{supr7}} \) (50º) | 22,566 | 30,210 | 35,343 | 37,474 | 39,1761 | 40,4554 | 42,1575 | 43,2201 | 43,8597 |
| \( m_{\text{supr9}} \) (60º) | 20,753 | 27,800 | 32,499 | 34,4587 | 36,025 | 37,1996 | 38,7659 | 39,7465 | 40,3322 |

4. Conclusion

Thus, at the magnetic field strength increase and constant MRF heating temperature in choking channels its added mass increases in a linear fashion. Simultaneously, at the MRF heating temperature increase its added mass decreases in a linear fashion as well. Therefore, when designing hydromounts with MRT, this effect is to be always taken into consideration. Considering these ratios, it is possible to find optimal engineering solutions when designing MRT choking channels.

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Acknowledgments
The work has been carried out at the expense of Russian Science Foundation (project №15-19-10026).