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RESEARCH ARTICLE

Development and Testing of a Closed Loop Feedback Controlled Magnetorheological Fluid Anti-vibration Mount for Onboard Naval Applications

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ABSTRACT

An intelligent semi-active anti-vibration mount using a magnetorheological (MR) fluid is designed and developed for onboard naval applications. The MR mount consists of a load bearing elastomer, MR fluid chamber; MEMS based vibration sensor and a controller for closed loop feedback mechanism. The controller regulates the solenoid current in the MR fluid chamber, which in turn regulates the flow of MR fluid through the valve. Comparison of the performance of MR mount with a passive resilient rubber mount shows that the former provides 7 dB extra damping at resonance compared to the later and the isolation of MR mount starts at 10 Hz compared to 50 Hz by rubber mount. This mount can operate in real time, passive and active modes by using a closed loop feedback control mechanism. The efficacy of the mount for outdoor applications is evaluated by characterising the mechanical, environmental, electrical and electromagnetic properties as per MIL-17185, JSS-55555, and IEC 61000 standards and found to be superior compared to passive mounts. The mount is evaluated for onboard applications in INS Ranvijay.

Keywords: Magnetorheological fluid, semi-active suspension, semi-active mount, vibration isolation, magnetorheological fluid mount

1. INTRODUCTION

Dynamic properties of magnetorheological fluid are extensively utilised worldwide to develop various smart/ intelligent devices[1-11]. These devices supersede their conventional counterparts in term of improved and better control of desired performance and functionalities. Some of the applications of magnetorheological fluids are in field of torque transfer devices, brakes and mirror/lens polishing. But the applications where the MR fluid devices have excelled are in field of dampers and mounts[12]. In this line, NPOL has designed and developed MR fluid based anti-vibration mount using the MR Fluid developed and patented by the authors[13-16]. By using these mounts reduced vibration signature could be achieved for improving the stealth characteristics of the vessel.

A major challenge in designing mounts is to make them statically stiff and dynamically soft. Elastomeric mounts are rubber-to-metal bonded elements that are widely used for a variety of industrial applications[17-18]. The dynamic stiffness of an elastomeric mount increases with frequency; therefore, stiffening the mount to achieve a better interfacing results in high dynamic stiffness and poorer isolation at the excitation frequency[19]. Reducing the dynamic stiffness requires a smaller static stiffness and lower ability to hold the structures together. To overcome these drawbacks of elastomeric mounts, fluid mounts are often used to provide a better compromise between the static and dynamic requirements of the mount[19].

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Passive rubber mounts have been widely developed and commercialised to support static load and isolate imposed vibration. The primary function of the passive mount is mainly to filter high frequency vibration. Passive hydraulic mounts are developed to meet large dynamic stiffness requirements in the resonance of low frequency domain[17-19]. The hydraulic mounts have high damping. Thus, the vibration isolation efficiency in the non-resonant domain is worse than that of the rubber mount. The damping and stiffness of the passive mounts are not simultaneously controllable to meet imposed performance criteria.

To overcome the limited performance of the passive mounts, active mounts have been widely undertaken. These are normally operated by using external energy supplied by actuators to generate forces on the system subjected to unwanted vibration. Various kinds of actuators, such as electromagnetic actuator, hydraulic servo actuator, and piezoelectric actuator have been applied to the design of active mounts[20]. The most common problem associated with the active mounts are extremely high power consumption, non-reliability and poor MTBF. The semi-active mount is the one that cannot inject mechanical energy into the controlled structural system, but can adjust damping or stiffness to reduce unwanted vibration of the system. The tunable semi-active mounts have been designed by incorporating fixed orifice valves, charged by field-responsive MR fluids[12]. The mount offers both passive as well as active damping. It will automatically switch from passive to active mode whenever the vibration level exceeds a threshold value which is programmed in the controller[21-23].

2. CLOSED LOOP FEEDBACK CONTROLLED MR FLUID ANTI-VIBRATION MOUNT

The glass view and photograph of the developed closed loop feedback controlled MR anti-vibration mount with relevant parts are as shown in Fig. 1. The mount can be roughly divided into two elements viz. spring and dashpot. The spring element in the top cover of the mount which is a truncated rubber cone 'A' which undergoes static deflection due to the weight of the structure or machinery mounted on it. Also the top rubber cover undergoes dynamic deflection under vibrations. The rubber is designed such a way that it needs to be statically stiff and dynamically soft for obtaining better isolation and damping. The rubber element is the load bearing member, which determines the maximum load carrying capacity of the mount. It also provides damping and isolation of non-resonant high frequency vibrations originating from the structure or machinery. The dashpot element consists of piston cum mounting rod, orifice, solenoid coil and flux guide enclosed in the casing. When mounted machinery or equipment vibrates, the piston cum mounting rod 'B' connecting with the rubber element also under goes to and fro motion from its mean position. When the piston moves down, the pressure in the lower chamber builds up that pushes the MR fluid 'C' through the orifice 'D' into the upper chamber 'E'. The restricted flow of MR fluid through the orifice generates resistive force which accounts for the damping offered by the mount. The damping force is proportional to the viscosity build-up of the MR fluid occurring in the orifice around the flange 'F'. The viscosity build-up is proportional to the magnetic field being generated by the solenoid situated radially concentric with the piston-cum mounting rod and stationed between two flange situated at the top and bottom of the solenoid. The flange guides the magnetic field generated by the solenoid 'G' in such a way that the magnetic flux passes through the orifice containing MR fluid perpendicular to the piston movement.

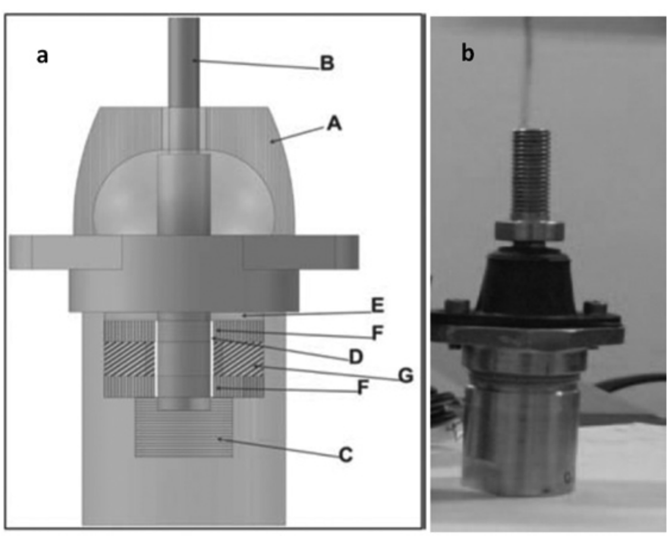

Figure 1. (a) Schematic of MR mount showing different parts; A-Truncated Rubber Cone, B-Piston-cum-mounting rod, C-Lower chamber of MR fluid, D-Orifice, E-Upper chamber of MR fluid, F-Flange guides, G-Solenoid (b) Photograph of a 60 kg load rated MR mount.

The block diagram of the system is as shown in Fig. 2. The amount of current to be supplied to the solenoid for real time operation needs to be proportional to the input vibration sensed by the sensor 'I' connected to the structure or machinery 'H'. The sensor provides signal to the control unit 'J' which draws the required current from the DC power supply unit 'K' based on the inbuilt algorithm in the control unit. The closed loop mechanism is achieved by use of MEMS accelerometer (Free scale Semiconductor Make MMA7261L) and electronic controller unit consisting of analog to digital converter and high power MOSFET drive unit and microcontroller (Microchip make PIC18F458) with control algorithm. The accelerometer picks up the vibrations generated in the machinery and the signal is send to control unit. The analog to digital convertor converts the accelerometer signal to a micro-controller process able format. The accelerometer offers high sensitivity in the range of 800 mV/g with fast turn on time which enables to transmit very small level of changes in the vibration amplitude to the control unit. The control algorithm embedded in the microcontroller determines the current required to be supplied to the MR mounts through high power MOSFET drive. Then MOSFET drive draws power from a transformer based 12V DC power supply unit and sends to the mounts. Thus the damping characteristics of the mount made proportional to the disturbing vibration by a closed loop feedback mechanism.

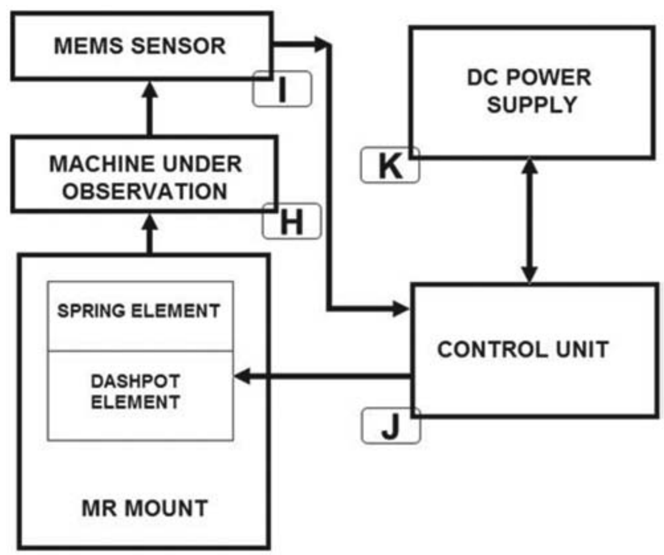

Figure 2. Block diagram of the MR closed loop feedback controlled anti-vibration mount.

3. DESIGN AND DEVELOPMENT METHODOLOGY OF MR MOUNTS

3.1 Non Dimensional Analysis

The non-dimensional analysis model of the MR mount utilizes four non-dimensional parameters: Bingham number, non-dimensional damping force, dynamic range, and non-dimensional geometric parameter defined as the ratio of the piston radius to the annular gap size. By imposing equality constraints on required damping force and dynamic range of the vibration model, the principal design parameters, such as shear length is determined from the non-dimensional analysis.

The cross section area showing various parts and notations of the mount used in non-dimensional analysis of MR mount are as shown in Fig. 3.

The following gives the sequential steps for the design of the MR mount:

1. specification of the piston velocity (V_p) knowing the frequency and amplitude of the vibration (design requirement),
2. the Bingham-plastic properties of the employed MR fluid (τ_y, η) to be known (τ_y= Shear yield stress, η= viscosity of the MR fluid),
3. calculation of the Bingham number $\phi_c = (\tau_y\ h/\eta V_p)$ by the substitution of τ_y and η of step (2), and considering appropriate gap size h. ϕ_c is the ratio of the dynamic yield shear stress to the viscous shear stress,
4. calculation of the non-dimensional force Φ_F which is given by

$$\phi_F = A\phi_r^3 + \phi_r\left(\frac{B}{6}\phi_c + C\right) \quad (1)$$

$$\Phi_F = F_{mr}/(6\pi\ \eta\ V_p L) \quad (2)$$

$$\phi_C = (\tau_y\ h/\eta V_p) \quad (3)$$

$$\phi_r = r/h \quad (4)$$

where r is piston radius, h is gap size, η is fluid viscosity, L is shear length, V_p is piston velocity and A, B and C are non-dimensional correction factors.

5. determining the $\Phi_{F,}$ by substituting the $\phi_{r,}\ \phi_C$ and correction factors,
6. damping force due to MR effect is predicted by suitable substitution in Eqn. 2.

By using the non-dimensional analysis the parameters for the design of MR mounts are finalised as shown in Table 1.

3.2 Parametric Modelling

Parametric modelling of the MR mount was done in CATIA modelling tool. Parametric modelling is carried out to ensure proper assembly of the component and to confirm that no interfering motions are occurring in the mounts

3.3 Electromagnetic Coil Analysis

ANSYS electromagnetic solution is used to compute solenoid parameters such as the current density and number of turns, the current, and the coil area. The contours of magnetic flux intensity obtained using Ansys Emag ® is shown in Fig. 4 and it shows the magnetic flux direction and intensity.

3.4 Design Outcomes

Designing was done for 60 kg and 120 kg MR mounts and parameters for fabrication of both mounts are listed Table 2. These parameters are used for generation of the engineering drawings of the MR mounts. The developed MR mounts with its complete accessories are as shown in Fig. 5.

Table 1. Result of non-dimensional analysis values for 60 kg MR mount

Name	Variable	Units	Value
Frequency	f	Hz	20
Amplitude	A	m	0.001
Velocity	V	m/s	0.1257
Shear length	L	m	0.01
Gap size	h	m	0.001
Piston radius	r	m	0.006
Plastic viscosity	μ	Pa.s	0.1
Yield stress	τ	Pa	10000
Damping force	F	N	28.53

Table 2. Various fabrication parameters for MR mounts

Parameter	Fabrication parameters	
	60 kg mount	120 kg mount
Shear length, L (mm)	10	16
Piston radius, r (mm)	6	7
Gape size, h (mm)	1	1
Damping force, F (N)	28.53	62.32
Coil area, A (mm)	$40*10^{-6}$	$86.4*10^{-6}$
No. of turns, N	120	200
Magnetic field intensity, H (amp-turns/m^2)	$1.37*10^{5}$	$3.3*10^{5}$
Magnetic flux density, B(T)	1.475	2.357
Foot print of mount, mm (height X diameter)	123 X 46	177 X 55

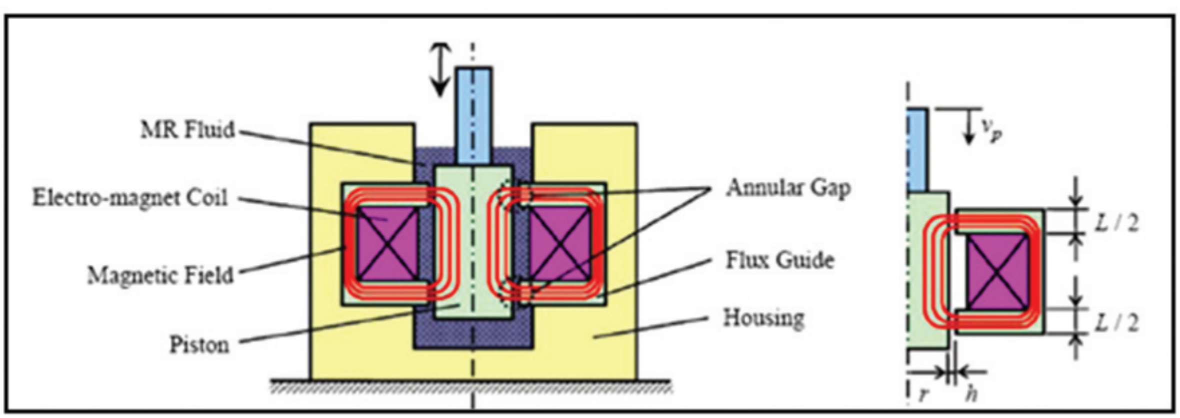

Figure 3. Non-dimensional analysis model of MR mount.

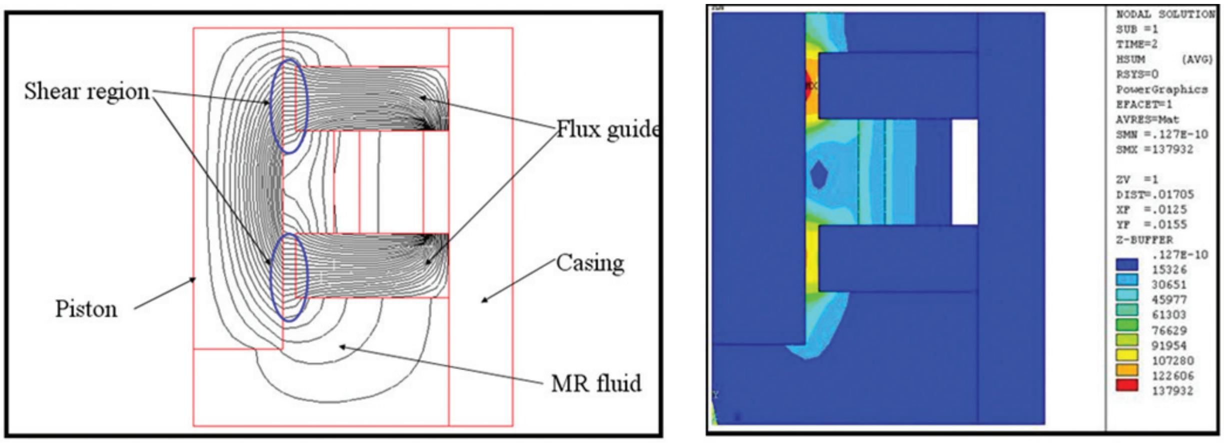

Figure 4. Magnetic flux lines and magnetic flux intensity in MR mount as obtained from Ansys Emag ® analysis.

Figure 5. MR mounts with controller unit, MEMS sensor and power supply.

4. TESTING AND EVALUATIONS

Based on the functionality and service conditions of the semi active mount developed following tests are conducted at various accredited laboratories such as CQEA, Bengaluru, BISS, Bengaluru, ETDC, Bengaluru, CPRI, Bengaluru, INS Shivaji, Lonavala and onboard INS Ranvijay by MTU of Indian Navy.

4.1 Vibration Transmissibility and Resonance Frequency

The developed MR mounts were tested for its functional performance by simulating real service conditions. Four MR mounts were placed on an electromechanical shaker by connecting it between two mounting plates viz. bottom plate and top plate to provide with vibration of known frequency and amplitude. On the top of this arrangement, 240 kg Mild Steel dead load was placed to simulate a machinery weight. The MEMS vibration sensor was bonded on the top of the dead load and connected to the control unit. The control unit was connected to the mounts. An additional connection from the control unit was established with a DC power supply unit that provides required current to the MR mount depending upon the requirement. Various parameters in the measurements such as the number of MR mount, dead load on the top of the mounts, the amplitude of the vibration generated by the electromechanical shaker, the frequency range of the electromechanical shaker etc. were varied to study the effect of these parameters on the performance of the mount. The controller unit was also switched OFF and ON during various measurements to evaluate the effect of the closed loop feedback mechanism. Figure 6 shows the test setup for carrying out vibration transmissibility test and Fig. 7 shows the transmissibility results with controller in ‘Off’ and ‘On’ position and Fig. 8 shows a comparison of performance of MR mount with respect to conventional used rubber mounts.

4.2 Static Load - Deflection Test

Static load deflection studies were carried out to study the linearity in the deflection of the MR mount for its rated load. This is important to establish the linear damping characteristics and rated load bearing capacity of the MR mounts. The test setup and result are as shown in Fig. 9. The mount can take 60 kg load with a deflection of 4 mm.

4.3 Vibration Endurance Test

Vibration endurance tests were conducted on 60 kg rated mount at M/s Bengaluru integrated systems and solutions, Bengaluru. The tests were conducted as per MIL-STD-167 by

Figure 6. Experimental Set-up for carrying out vibration transmissibility tests.

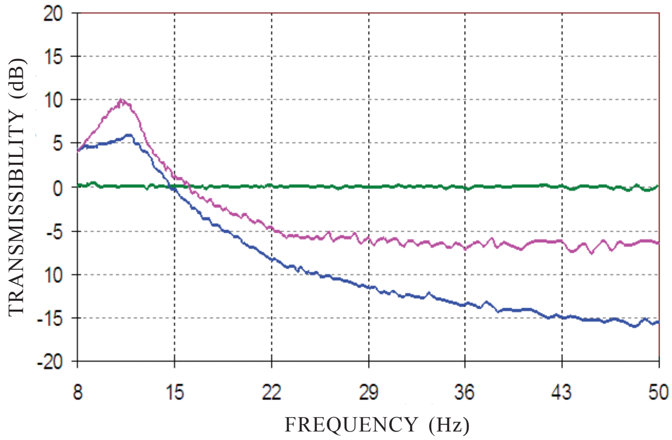

Figure 7. Vibration transmissibility of MR mount in (1) Passive mode [Controller – 'Off' mode] (shown in pink)(2) Active mode [Controller – 'On' Mode] (shown in blue).

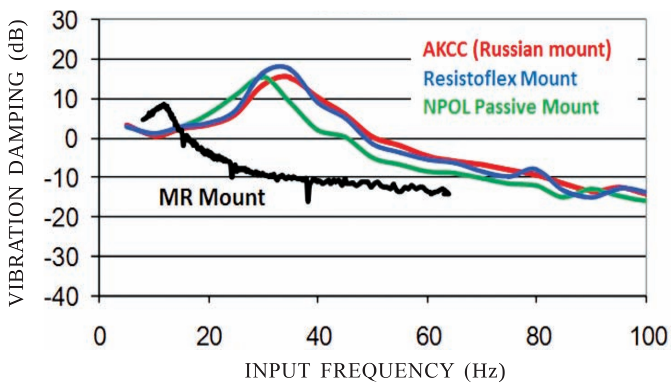

Figure 8. Vibration transmissibility results, the isolation for MR mount starts from 15 Hz while for passive resilient mount starts from 50 Hz and above.

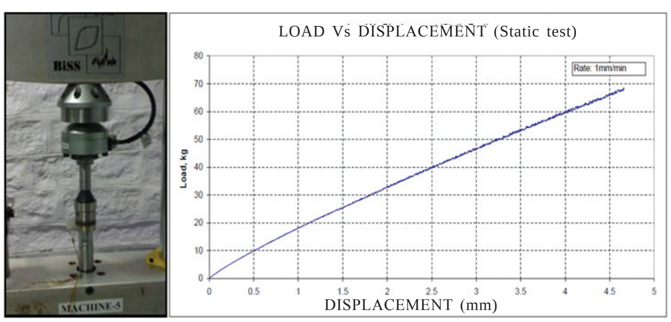

Figure 9. Static Load Deflection of MR mount measured at BISS, Bengaluru.

subjecting the mount 5 lakhs cycles of loading. Additionally the controller unit was also separately subjected to vibration endurance test as per JSS 555555 standard by accelerating at various 'g' values for about 6 h. The performance of the mount and controller were tested after the endurance tests.

4.4 Shock Endurance Tests

Shock Endurance tests are essential to ensure shock tolerance of the device. 70 g shock impulse for 8 ms was imparted using a 500 kg impact hammer on the MR mount assembly with the load and MR mounts were kept in OFF and ON conditions. Observations were made on the performance of the mount before and after the shock tests to ensure that the device continues to perform satisfactorily. The tests were conducted as per JSS-55555 standards at CQAE, Bengaluru. The vibration transmissibility test was conducted after shock test to check any property deterioration. The experimental setup is shown in Fig. 10.

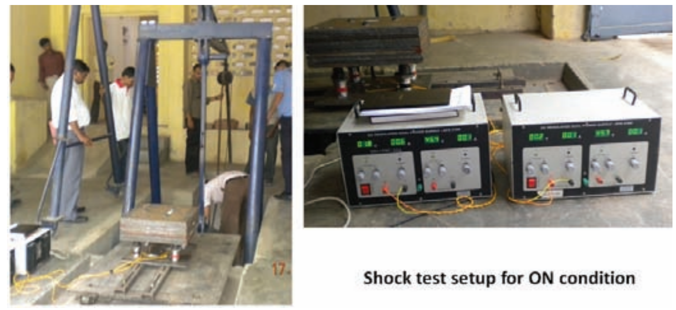

Figure 10. Shock Test on MR mount assembly with controller on and off conditions.

4.5 Salt Fog Test

Salt fog test has been conducted as a part of environmental test to evaluate the corrosion resistance, cracking, chipping, pitting or scaling of mount and its performance thereof. Initially salt spray test was conducted on 60 kg MR at LRDE, Bengaluru and based on the results obtained modifications were incorporated to improve the corrosion resistance of the mounts. The tests were conducted as per MIL-STD-17185A and JSS-55555 standards.

4.6 Oil Contamination Tests

This test is conducted to ensure the survivability of the MR mounts while operating in oily and hydraulic fluid environments. The oil contamination test was conducted at CQAE(WE) Bengaluru. The tests were conducted as per MIL-STD-17185A and JSS-55555 standards. No performance degradation in the load - deflection or electric resistance were observed in the mount after the test.

4.7 Low Temperature Test

Cold Storage Tests are conducted to ensure the operation of MR mount at low temperatures without any degradation of performance. Test was conducted at CQAE(WE), Bengaluru. The tests were conducted as per MIL-STD-17185A and JSS-55555 standards. There was no performance degradation observed in the mount due to cold temperature exposure.

4.8 Electromagnetic Tests

Various electromagnetic interference tests were conducted as per IEC 61000 standard to ensure that the EMF of the mount does not interfere with other electronic device or the performance of the mount will not be affected by presence of strong electromagnetic signals. Tests like electromagnetic radiation disturbance measurements, electrostatic discharge immunity measurements, immunity to conducted interferences, power frequency magnetic immunity tests, etc. were carried out. The tests were conducted at ETDC, Bengaluru. It was found that the device neither leaves any electromagnetic trace nor its performance will not affected by external magnetic field. Figure 11 shows the experimental set-up.

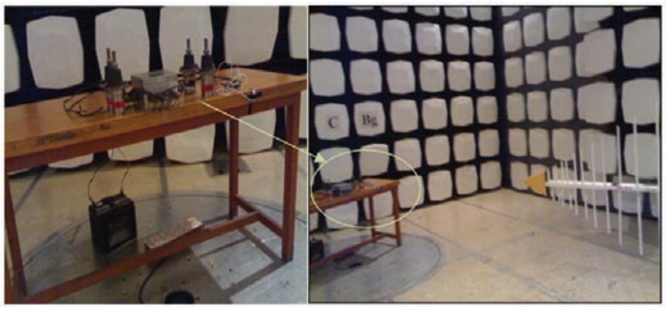

Figure 11. Experimental Setup for Electromagnetic radiation disturbance measurement in the microwave chamber.

4.9 Field Trials in INS Shivaji, Lonavala and INS Ranvijay

As part of user evaluation, the MR mount is independently tested at INS Shivaji, Lonavala for one of the pumps used in ships for pumping sea water for AC tower cooling. The performance of the mount is compared with commercial mount (Resistoflex). MR mount has 30 per cent less vibration transmissibility compared to commercially available one. It is observed that the mount is more effective in vibration damping and isolation in low frequency region where commercially available mounts fail to act. The test setup adapted at INS Shivaji is shown in Fig. 12. Sea water pump used for cooling AC tower in INS Ranvijay was installed on MR mount and its performance were tested and compared with AKCC Russian mount. The pump was originally fitted with AKCC Russian mount. The overall vibration attenuation level of the pump fitted with both mounts was compared and the values are shown below. It is seen that MR mount has better attenuation at all frequencies except a narrow band of frequency between 500 Hz to 800 Hz. The MR mount is under operational onboard INS Ranvijay continuously for more than 18 months. The performance comparison is as shown in Fig. 13.

5. CONCLUSION

In order to control and isolate low frequency vibrations, an intelligent mount based on MR was developed. The mount consists of a patented MR fluid and a closed loop feedback control mechanism. The mount is tested for its resonance frequency, vibration transmissibility, endurance, active and passive modes of operations etc. as per various MIL standards. The vibration transmissibility characteristics of the MR mount in active and passive modes shows that the resonance frequency of the mount is10 Hz and vibration isolation starts from 14 Hz when the controller is in semi-active mode. The comparison of the performance of MR mount with passive resilient rubber mounts shows that the former provides 7 dB extra damping at resonance compared to the latter and the isolation of MR mount starts at 14 Hz compared to 50 Hz by the rubber mount.

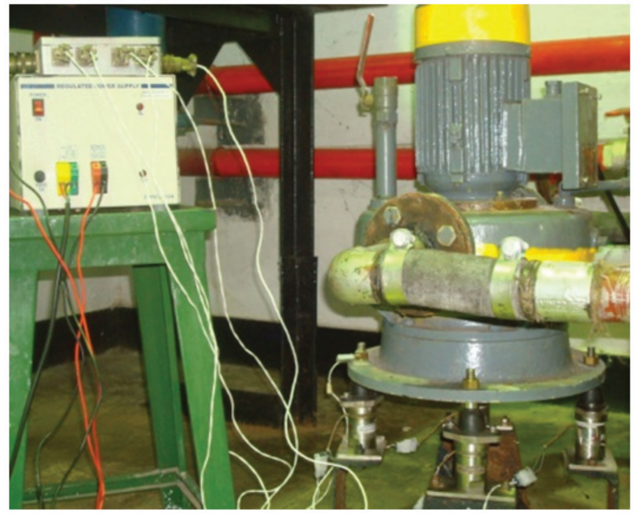

Figure 12. Water pump installed on MR mounts at INS Shivaji, Lonavala for evaluation of MR mounts.

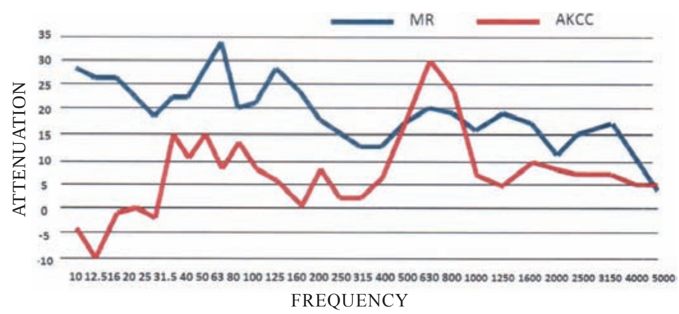

Figure 13. Testing Result on-board INS Ranvijay - Comparison of vibration attenuation of MR mount (Red) with AKCC Russian mount (Blue).

Environmental tests such as salt spray, cold chamber, oil immersion etc. are conducted as per JSS 55555 standards and electrical and electromagnetic characteristics are tested as per CISPR11 class-B IEC 61000 standards. All the above tests show that the newly designed intelligent mount is suitable for low frequency vibration damping and isolation and has several advantages over the commercially available passive rubber mounts. Currently available passive mounts are effective at higher frequencies and ineffective at low frequencies. The MR mount technology can fill the gap of vibration isolation and damping at low frequencies. Apart from naval applications, the MR mount can find application in precision experimental setup where zero vibration tolerance is required, high precisionanti-vibration tables, mounting on various household equipment, gun recoil systems, etc.

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Mr Shiv Kumar is post-graduate in Chemical Engineering from IT BHU, Varanasi (currently IIT, BHU, Varanasi) and joined NPOL, Kochi in 2002. He has been working in the field of sonar and transducer related material development and testing. He field of interest is smart materials based devices and underwater structural composites. Apart from filing 4 patents, he also has 2 international journal publications, around 20 conference papers to his credit.