A Seismic Isolation System for Lightweight Structures based on MRE Devices

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***Abstract* — In this paper, the usefulness of magneto-rheological elastomeric devices for seismic protection of lightweight structures, containing sensitive equipment, is investigated. In particular the isolation device is considered in combination with ball transfer units (BTU) which have the task of supporting the equipment weight. In this way the magneto-rheological device can be chosen without fearing for its stability. The isolation system can combine the advantages of passive systems, which can operate even without of external energy, with those of active systems that can control the structure motion with the aim of reducing the accelerations.**

***Index Terms*— Seismic isolators, magneto-rheological rubber, nonlinear dynamics, semi-active control.**

I. INTRODUCTION

Passive seismic isolation of structures is achieved by decoupling the dynamic structure response from the ground motion. The decoupling is obtained through the interposition of devices with low horizontal stiffness and high dissipative capacity; in this way the structure has a fundamental frequency much lower than the non-isolated structure and of the main frequencies ground motion.

The reduction of the energy transmitted, from the ground to the structure, is so obtained through the filtering of the components at the higher frequency of the seismic motion, generally characterized by a higher energy content; furthermore, energy dissipation capacity is increased and is concentrated outside of the structure in correspondence of the isolator devices.

Isolators shall have the capability to support the weight of the structure and must exert a restoring force to re-centre structure. The steel-reinforced elastomeric isolators (Fig. 1) meet these requirements and are commonly used for passive seismic protection of structures. They are made up of rubber layers alternated with steel sheets, whose number and size are chosen to obtain a high vertical stiffness, in order to avoid large compliances due to the structure weight, and a low horizontal stiffness to shift the natural period away from the period range having the most of earthquake energy.

Fig.1. Elastomeric steel-reinforced isolator

However, in the case of lightweight structures, to achieve low values of the fundamental frequency, the elastomeric devices should have very small cross-section and are so inadequate to support the structure weight. In these cases the weight could be supported by sliding or rolling devices, so that the elastomeric elements should only exert the re-centering function; with this configuration the elastomeric element can be freely chosen to meet the desired fundamental frequency without fearing for its stability.

This criterion was adopted for WRS-BTU isolators [1] constituted by a wire rope spring for the restoring force and by a ball transfer unit to sustain the structure weight (Fig. 2).

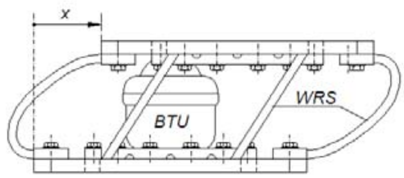

Fig. 2. WRS-BTU isolator.

These insulators can be adopted for lightweight structures such as cabinet or shelter; for the presence of wire ropes it has a hysteretic non-linear behaviour [2], modelled with the Bouc-Wen theory [3]. Tthey have been tested to isolate a laboratory structure (rigid and with tunable inertial characteristics) displaced on a shaking table [4]. The tests have been highlighted a good isolation efficiency even due to the intrinsic damping characteristics of WRS springs [5].

Passive insulation systems are "open-loop" control systems as their action (the restoring force) is independent from the output (state of the isolated structure). The control law is a way of filtering the higher frequency seismic components.

The dynamic process can instead be favorably adjusted by changing the restoring force, during the seismic event; an active control (closed-loop control) may be adopted to reduce the acceleration of the isolated structure, using an external energy source capable of exerting a force, whose intensity depends on the system state (feedback).

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II. CONTROL ACTION

Control action can be provided by an actuator or adopting a *smart control device* (or semi-active device) that assumes the positive aspects of passive and active control devices. A semi-active control strategy is similar to the active control strategy but, the control actuator does not directly apply a force to the structure but, it is used to control the properties of a passive energy device.

Examples of semi active devices are the magneto-rheological (MR) ones. MR dampers may adjust their damping characteristics by applying a suitable magnetic field that has the effect of changing the fluid viscosity [6]. Such devices have been widespread even in other areas [7]. In MR rubbers the magnetic field induces a variation of the material stiffness [8].

In recent years, many algorithms have been developed to control semi-active (SA) devices; the most used are reported below.

The most elementary method of formulating algorithms to control SA devices is to directly observe one or more response quantities to be protected and, thus, activate or not the device on the basis of the interpretation or of the influence that the device has on the same magnitudes of response (typically displacements and accelerations).

The device can be activated if the response exceeds a threshold value of the displacement [9] or of the absolute acceleration [10] or both, relative displacement and the absolute acceleration [11], taking into account that an increase of the damping, in general, involves a reduction of displacement but an increase of the transmitted force.

Other control methods are based on the observation of others response magnitudes. For example in [12], a change of the support stiffness move the system away from the dominant frequency of excitation while in [13] the damping value is selected to ensure a constant force equal to the permitted limit.

For base excited one d.o.f. systems, the *Sky-Hook damping* is the ideal damping of a linear viscous damper working with respect to the absolute speed (instead of the relative one), ideally connecting the mass to the sky. This damping system [10] is very favorable to reduce the transmissibility (i.e. the ratio between suspended mass and ground motion amplitude).

Fig. 3 compares the transmissibility in case of conventional and Sky Hook damping. Unlike what happens with the conventional damping, the Sky-Hook damping involves a transmissibility reduction for all the exciting frequencies. This is an important feature in the design of active isolation systems, which are called to reduce the absolute motion for which the high frequencies play an important role.

The algorithms adapted from the theory of optimal control are based on the optimal control theory [14], in which is defined a Performance Index (PI), which is a quantitative and objective measure of the control effectiveness.

The energy approach algorithms are based on the balance energy equations; the most intuitive way is to maximize the dissipated energy [15] .

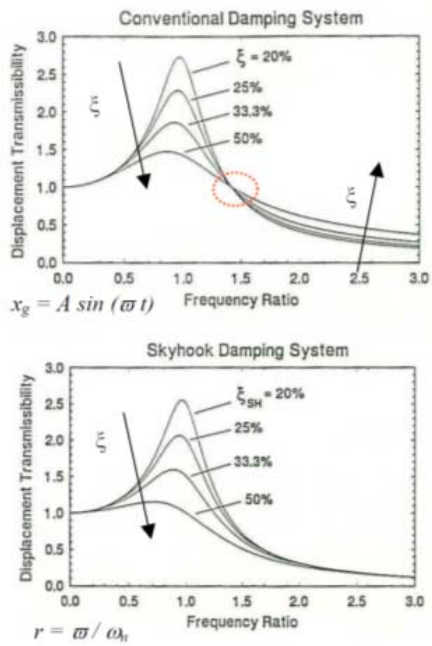

Fig. 3. Sky-Hook Damping Control

III. MAGNETORHEOLOGICAL ELASTOMER

The magnetorheological elastomers (MRE) are compounds in which are suspended magnetic particles in a non-magnetic solid matrix or gel. The mechanical and rheological properties of these materials, containing magnetizable particles (size 3-10 μm), may be reversibly changed by applying a magnetic field. Experimental tests have shown that the physical property which undergoes a significant variation as a function of the magnetic field is the elastic modulus [16] while the damping undergoes minor changes [17]. In this way it is possible the realization of elements with controllable stiffness.

If the latter is carried out by immersing the mixture in a suitable magnetic field, the iron particles will tend to align and forming an anisotropic elastomer, otherwise in absence of magnetic field the elastomer turn to be isotropic. The use of an MRE isotropic or anisotropic depends on the application.

Magnetorheological effect refers to the variation of the shear modulus, G, with respect to the value assumed in the absence of magnetic field. This effect is maximized for particle concentrations in volume ranging from 20% to 30% [16]. The magnetic field may realized by means of solenoids; the elastomer will be part of the magnetic circuit whose presence will influence shape and size of isolator.

Shear modulus depends on the module of the matrix, G_0, and on the amount of iron powder. To estimate G value as a function of the volume percentage, ϕ, of iron particles the following formula can be used [18]:

$$G = G_0 (1+1.25\,\phi + 14.1\,\phi^2) \qquad (1)$$

MRE dynamic behavior can be described by means of the Chen model [19] schematically represented in Fig. 4 where G_1, G_2, and η are the parameters of the Standard Linear Model used to model the viscoelastic behavior of the rubber matrix [20] while G_m represents the modulus contribution depending on the magnetic field.

ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

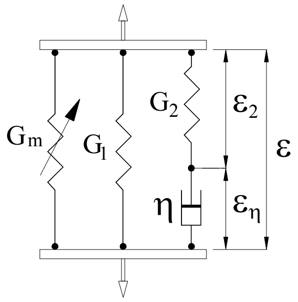

Fig. 4. MRE rheological model

Shear modules G_1, G_2 and damping η may be evaluated by means of the following formulas [20]:

$$\frac{G_1}{G_2} = A;\ \tan\delta_{\max} = \frac{1}{2\sqrt{A(A+1)}};\ \omega_{\max} = \frac{G_2}{\eta}\frac{1}{\sqrt{A(A+1)}} \tag{2}$$

Being ω_{max} the pulsation for which $tan\delta$ is maximal.

G_m may be determined starting from the shear stress τ_m expression:

$$\tau_m = \frac{\partial U}{\partial \varepsilon} \tag{3}$$

being [21] U the energy density dipole:

$$U = \frac{3\varphi(\varepsilon^2 - 2)J_p^2 V_p^2}{2\pi^2 \mu_0 \mu_1 d^3 r_0^3 (1+\varepsilon^2)^{5/2}}, \tag{4}$$

In (4) appears:

- $\mu_0 = 4\pi 10^{-7}$ N/A^2; $\mu_1 = 1$: the relative permeability of the medium;
- $J_P = \mu_0 M_P$: the dipole moment magnitude per unit particle volume;
- r_0 = distance between adjacent particles, d diameter of particle;
- $V_p = \pi d^3/6$ = volume occupied by particles.

Indicating with: $h = r_0/d$, and developing the derivative it follows:

$$\tau_m = \frac{\varphi(4-\varepsilon^2)J_P^2}{8\mu_0\mu_1 h^3 (1+\varepsilon^2)^{7/2}}\ \varepsilon \tag{5}$$

Under the hypothesis of particles spherical, homogenous, and aligned in perfect chains $h^3 = \frac{\pi}{6\varphi}$, remembering the law of Frohlich Kennely

$$M_P = \frac{(\mu_P - 1)M_S H}{M_S + (\mu_P - 1)H} \tag{6}$$

being M_S the saturated magnetization such that: $\mu_0 * M_S$ =2.1T and μ_P=1000 is the permeability of ferromagnetic materials, H is the magnetic field strength.

It is possible to write:

$$G_m(H) = \frac{6\,\varphi^2 \mu_0 (\mu_P - 1)^2 M_S^2 H^2 (4-\varepsilon^2)}{8\pi\,\mu_1 [M_S + (\mu_P - 1)H]^2 (1+\varepsilon^2)^{7/2}} \tag{7}$$

IV. Isolation System Based on MRE Elastomeric Device and BTU

In the following is evaluated the possibility to develop a seismic isolation system for lightweight structures based on the use of BTU for the sustenance of the structure weight and MRE element for the horizontal restoring force. These elements work as passive devices in absence of magnetic field; this characteristic is particularly appreciated since the active systems are often not adopted because they require a source of external energy that could fail just in the moment of need. This devices combines the positive aspects of the passive elastomeric isolators with the advantages of controlled systems.

In particular the insulation system is made from 4 BTUs, arranged at the vertices of the cabinet base area (Fig. 5), and two MRE elements placed in the central position of the base. These two elements are designed to provide a natural frequency for the cabinet of about 1 Hz for the horizontal translations and for yaw rotation.

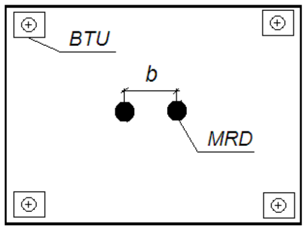

Fig. 5. Isolation system scheme

A. BTU rolling support

BTU are commercially widespread support constituted by an omni-directional load-bearing spherical balls mounted inside a restraining fixture, having the task to bear the structure weight with a neglecting vertical deformation; it allows the structure to translate along any horizontal direction with low friction (Fig. 6).

The device can be mounted in ball-up configuration, i.e. with the main ball in contact with the intrados of the upper plate so that dust or debris cannot settle on the rolling surface and cannot affect the regular rolling of the main ball.

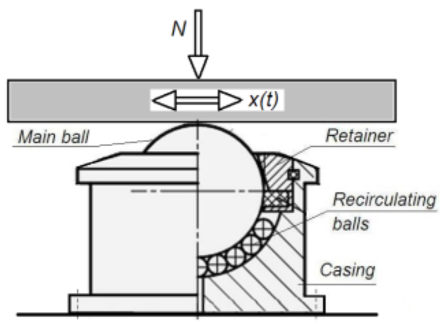

Fig. 6. Ball Transfer Unit (BTU) scheme.

The BTU rolling resistance depends on the vertical load acting on the main ball; the rolling resistance assumes a

ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

lower values if the vertical load increases up to the value for which all the recirculating balls are sufficiently loaded to ensure a rolling motion instead of a sliding motion. Over this value the friction coefficient grows with the vertical load (Fig. 7).

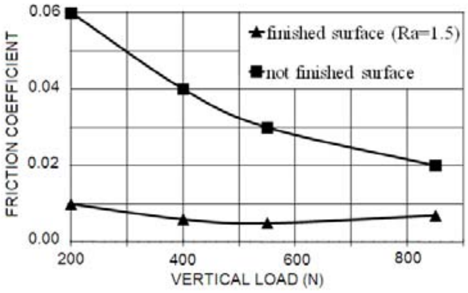

Fig. 7. BTU friction coefficiens vs the vertical load.

B. Elastomeric devices

Rubber isolators are widely adopted to isolate vibrations, both in the industrial and civil field, as they present a good level of damping (the equivalent viscous damping ranges between 10 and 30%) and can reach high level of shear strain (even up to 200%).

To determine the size of the two rubber elements, the magneto-rheological effect is neglected and a linear elastic behavior is considered for the rubber although it has a non-linear behavior and is subjected to deformations that cannot be considered of small amplitude.

Assigned the horizontal natural frequency for the cabinet, f_n, and being note its mass m, the horizontal stiffness k of the overall isolation system is:

$$K_{tot} = 4\pi^2 f_n^2 \cdot m\,. \tag{8}$$

The stiffness of each element is due to bending and shear contribution so that the overall stiffness is equal to:

$$k = \frac{1}{\frac{1}{k_b} + \frac{1}{k_s}} = \frac{1}{\frac{t^3}{12EI} + \frac{t}{GA}} \tag{9}$$

being E the Young modulus while I is the cross-section moment of inertia.

The shear contribution ($k_s = G\,A/t$) depends on the shear dynamic modulus G, on the cross section area A purified of any holes and on the height t of the isolator (or the sum of the thicknesses of the elastomer individual layers in case of steel-reinforced elastomeric isolators)

The rubbers usually adopted for isolators have shear dynamic modulus, G, ranges between 0.40 N/mm^2 (soft rubber; 50-55 ShA) to 1.40 N/mm^2 (hard rubber) for shear strain ranging between 100% and 200%. The value is also affected by temperature and aging (which produces an increase in stiffness of about 15% in 60 years), while it may be considered independent from the excitation frequency and from the vertical load applied. The applied vertical load affect, in a considerable way, the equivalent damping value; a doubling of the vertical load induces an increase on the damping of 50% - 100%.

MR rubbers generally have a matrix whose shear dynamic modulus can assume lower values (up to 0.1 N/mm^2).

The behavior of elastomeric isolators is defined by two geometrical factors:

- the primary form factor: $S_1 = A/L = D/4t$, being L the isolator lateral surface without applied loads. This factor controls the device vertical stiffness; to have a sufficiently high vertical stiffness it is good practice that S_1 is greater than 20;
- the secondary form factor: $S_2 = D/t$ that controls the stability of the device; generally it is assumed greater than 3 to avoid instability problems.

For cylindrical isolators, indicating with R the radius, form factors assume the following expressions:

$$S_1 = R/2t\,; \quad S_2 = D/t \tag{10}$$

For the presence of the BTU supports, the geometry of the elastomeric devices can be chosen without fear instability problems or deficiency of vertical stiffness. Therefore, it is possible to use isolators made up of low stiffness elastomeric compounds (even lower than $G = 0.10$ N/mm^2), containing ferromagnetic particles which in the presence of a magnetic field confer a higher stiffness values.

The stiffness can be maintained at the high values by means of the magnetic field generated by two permanent magnet. In this way the cabinet structures will not move if stressed by a small forcing action while, in the case of more severe forcing action, the magnetic field generated by means of a coil, will reduce the device stiffness with a greater benefit for seismic isolation.

The geometric dimensioning of the rubber device is determined considering the stiffness value that the device assumes for particle concentrations in volume equal to 20%.

Adopting a silicon rubber with G_0 = 0.15 N/mm^2 and $\phi = 0.20$, from eq. (1) it follows: G = 0.27 N/mm^2. Adopting two cylindrical elastomeric elements with the following diameter and height: d = 28 mm; t = 30 mm, it follows that each element is characterized by a horizontal stiffness k = 3.7 N/mm (with: K_b = 10.95 N/mm; k_s=5.58 N/mm); for a cabinet mass of 185 kg, the translational natural frequency will be equal to 1.07 Hz.

It must be noted that if the system under test is characterized by two vertical planes of symmetry, the centre of mass lies on the same vertical axis of the isolators stiffness centre; therefore the three cabinet planar vibrating modes are uncoupled and the ground motion (or the platform motion of a shake table) along one principal direction does not excite cabinet yaw rotation. Yaw natural frequency can be estimated considering that the structure mass moment of inertia, with respect to its vertical symmetry axis, is equal to about J=35 kgm^2 and that the yaw stiffness, provided by the isolators, is equal to:

$$k_\psi = 4\,k\,b^2 \tag{11}$$

being b the distance between each isolators and the vertical symmetry axis (Fig. 5). The yaw natural frequency is therefore:

ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

$$f_{\psi} = \frac{1}{2\pi}\sqrt{\frac{k_{\psi}}{J}} = \frac{b}{2\pi}\sqrt{\frac{4\,k}{J}} \qquad (12)$$

Eq. (12) allows to deduce the distance between the two isolator:

$$\mathrm{b} = 2\pi\, f_{\psi}\sqrt{\frac{J}{4\,k}} \qquad (13)$$

In particular, for: f_{ψ} =1 Hz; k=3700 N/m e J=35 kgm^2, it follows: b = 306 mm.

Finally it can be notated that BTU devices realizes an unilateral vertical constrain for the cabinet as they are unable to exert a downward reaction. Therefore, in case of high horizontal acceleration, BTU devices cannot contrast the cabinet overturn caused by inertial forces; even MRE insulators can counteract the cabinet overturning as they are arranged in the central part of the base and, in any case they do not have an extensional stiffness able to oppose the triggering overturning. For this reason the acceleration must not exceed the maximum value a_{max} for which a couple of devices exert null vertical reaction (Fig. 8). From the equilibrium condition, it follows:

$$a_{\max} = \frac{g}{2}\frac{p}{h} \qquad (14)$$

being p the distance between the BTUs along the motion direction and h the heigh of the center of mass.

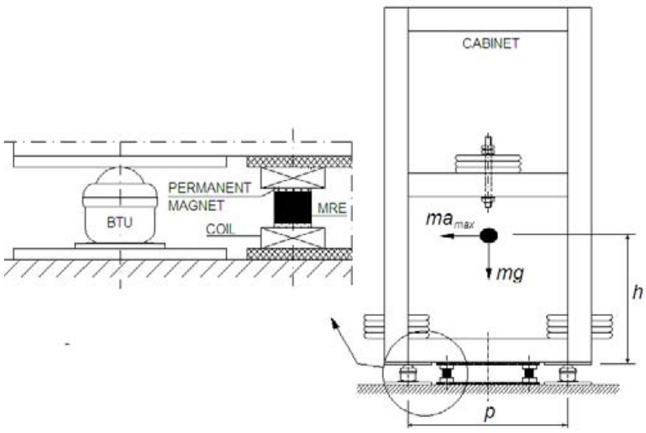

Fig. 8. BTU vertical reactions

The minimum cabinet p/h ratio is equal to 1.8 and therefore: a_{max} = 0.9g, that is greater than the maximum seismic acceleration (0.5g is a very high level seismic acceleration).

V. ISOLATOR ELECTROMAGNETIC SCHEMA AND CHARACTERISTICS

The MRE isolator (Fig. 9) is composed of four electromagnets, four permanent magnets and two magneto-rheological rubber elements. From an electromagnetic point of view, the two isolators are connected by means of two bars of ferromagnetic material.

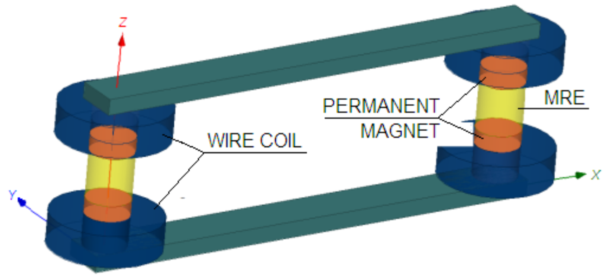

Fig. 9. MRE isolator scheme.

The control action is exerted by feeding the four coils; in this case the magnetic flux closes through the bars, as qualitatively shown in Fig. 10, and has the effect of reducing the stiffness of the two insulators.

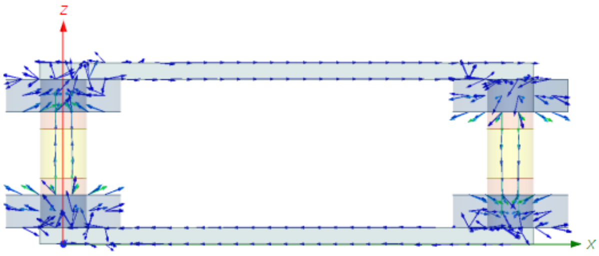

Fig. 10. Example of magnetic flux with coils in voltage.

If, instead, the coils are not in voltage, the insulators are only subjected to the field generated by the permanent magnets and the magnetic flux assumes the trend shown in Fig. 11

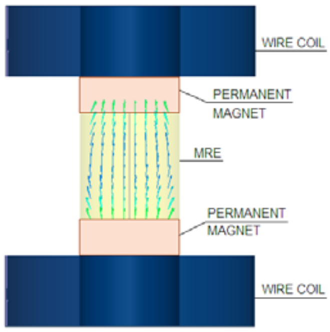

Fig. 11. Example of magnetic flux only due to the permanent magnet.

Permanent magnets must be chosen to maximize the shear modulus G when the coils are not fed. The shear modulus decrease when the coils are fed as the resulting magnetic field decrease with the current intensity. Fig. 12 and 13 show, respectively, the magnetic field magnitude without and with supply current to the coils

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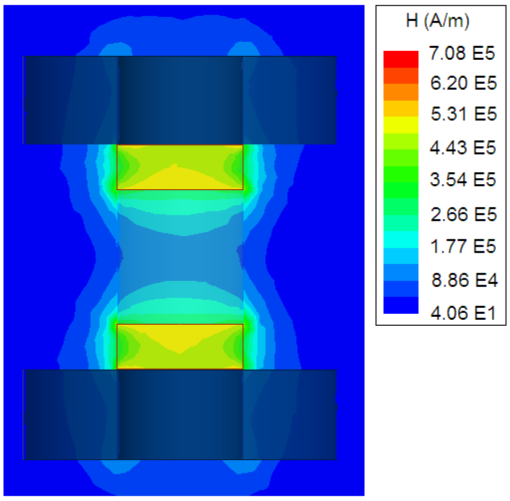

Fig. 12. Magnitude of Magnetic field with only permanent magnet.

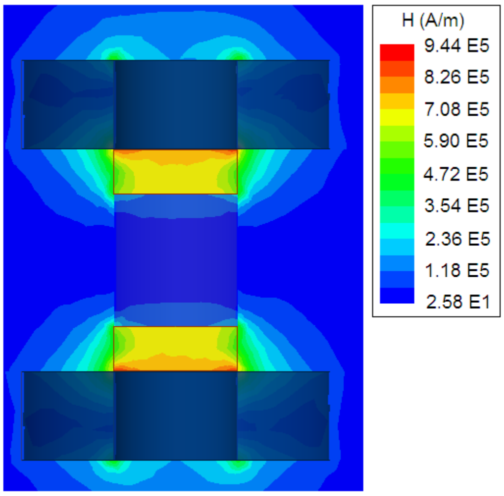

Fig. 13. Magnitude of Magnetic field in presence of supply to the coils.

Supposing that every coil have a winding of 3000 turns and that the current can vary in the range 0 A - 6 A, the corresponding variation of shear modulus G will have the trend reported in Fig. 14. Therefore it can be concluded that it is possible to modify, in a controllable manner, the overall stiffness of the isolator, reducing the shear modulus with the increase of the current intensity.

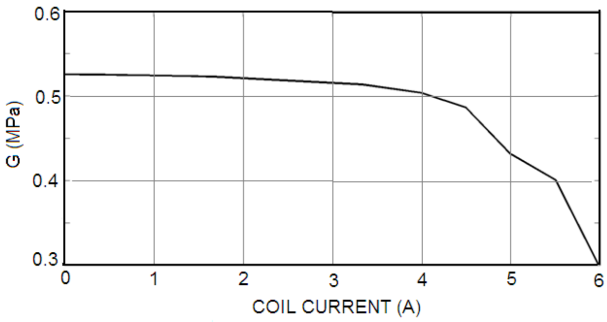

Fig. 14. Variation of G modulus

VI. Conclusion

An theoretical investigation on the feasibility of a seismic isolation system made up of a MR device and BTU supports has been presented. In the seismic applications the passive systems are often preferred to the active ones as they do not require an external energy contribution and are activated by the input motion. This configuration allows to overcome the diffidence towards seismic active isolators as they can operate as a passive isolator in case of lack of external energy.

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ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)