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Adaptive Electromechanical Tuned Vibration Absorbers and Their Application in Semi-Active Fluid Mounts

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ABSTRACT

An adaptive electromechanical tuned vibration absorber (ETVA) is developed consisting of a voice coil and a single degree of freedom mass spring system. The natural frequency of the ETVA is varied and tuned by addition of a variable capacitor. In this paper, the design, mathematical model, and experimental data of the ETVA is presented. Experimental data indicates that the natural frequency of the ETVA can be varied by 66% using capacitive shunting of the voice coil. Analytical studies have also revealed that if the wires of the voice coil could be replaced with room temperature superconductors, the natural frequency of the ETVA can be changed by a factor of 8 using a resistive shunting of the voice coil. The ETVA is then used in conjunction with a passive fluid mount to create a variable notch semi active fluid mount. Finally, the mathematical model and simulation results of the ETVA plus the passive fluid mount are described and presented.

INTRODUCTION

An adaptive Electromechanical Tuned Vibration Absorber (ETVA) is a semi-active vibration control device which is tunable and it has the ability of reducing undesired vibration at any desired frequency.

Here in this paper, an electromechanical tuned vibration absorber (ETVA) is introduced consisting of a voice coil and a single degree of freedom mass spring system. The natural frequency of the ETVA is varied and tuned by addition of an electronic circuit (RLC circuit). The design, mathematical model, and experimental data of the ETVA is presented and thereafter, the effect of changing RLC parameters in varying natural frequency of the tuned vibration absorber (TVA) is discussed.

Finally, the ETVA is used in conjunction with a passive single pumper fluid mount to create a variable notch frequency semi active fluid mount. The mathematical model and simulation results of the passive single pumper fluid mount plus the ETVA is then presented and discussed.

ELECTROMECHANICAL TUNED VIBRATION ABSORBER

In this section, the developed adaptive electromechanical tuned vibration absorber (ETVA) is explained in details. The ETVA consists of a mass, a spring, a voice coil, and a RLC electrical circuit. The RLC circuit is shunted to the voice coil and is used to change the natural frequency of the TVA [1,2]. A RLC circuit consists of a resistor, an inductor, and a capacitor element in series. Here in this paper, it is not intended to use all the three electrical elements simultaneously but only one at a time. Meaning, the coil will be connected to either a variable resistor, or to a variable inductor, or to a variable capacitor. Fig. 1 shows a picture of the developed ETVA which is fixed to a dynamic test machine.

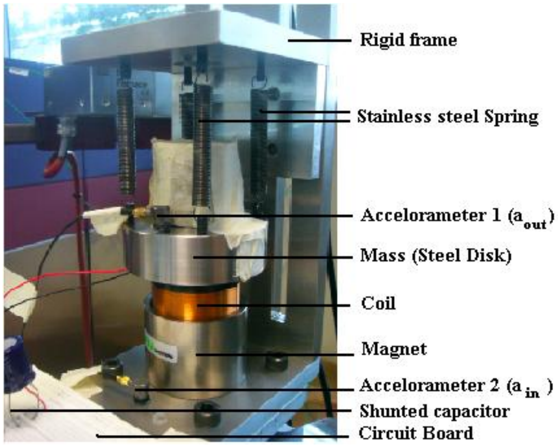

Figure 1. Adaptive Electromechanical Tuned Vibration Absorber (ETVA)

PHSYICAL MODEL

The schematic physical model of the ETVA is shown in Fig. 2 The math model consists of a mass (M) representing the mass of the moving coil plus the mass of the steel disk, a spring (K) representing the total spring rate of the four springs, and a damper (C) representing the overall damping of the 4 metal springs. Fig. 2 indicates that the moving coil can be connected to a variable resistor, or an inductor, or a capacitor to change the natural frequency of the TVA. As is shown, the permanent magnet and one end of the spring-damper are fixed to a rigid frame. Mass-spring-voice coil system is stimulated by a sinusoidal acceleration which is applied to the rigid frame. Two accelerometers are connected, one to the mass (M) and one to the rigid frame. The accelerometer which is connected to the mass (M) measures the output acceleration (a_{out}) and the other one which is connected to the rigid frame measures the input acceleration (a_{in}).

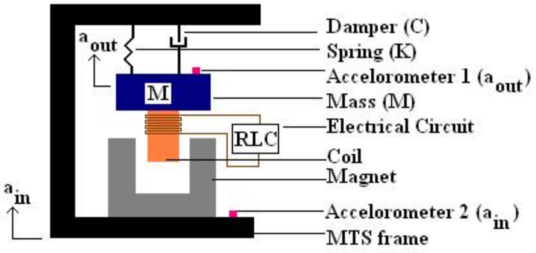

Figure 2. Physical model of the ETVA

Voice coils consist of a wire winding (coil) and a magnet. The coil can be modeled as an inductor and a resistor, so when a RLC circuit is added to the coil, the model of the coil plus the RLC circuit can be as follows, see Fig. 3:

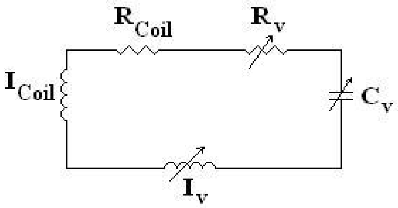

Figure 3. Coil Model plus the RLC circuit

Since the ETVA involves multiple energy domain system (electrical, mechanical and magnetic), bond graph modeling technique is used to derive the constitutive equations of the system [3]. Fig. 4 shows the bond graph model of Fig.2.

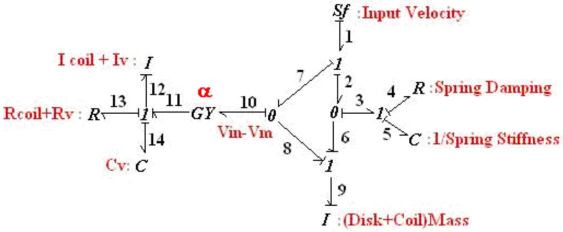

Figure 4. Bond graph model of Fig. 2

The following state-space equations are derived from the bond graph model of Fig. 4:

$$\dot{q}_5 = Sf_1 - \frac{P_9}{I_9} \tag{1}$$

$$\dot{p}_9 = (Sf_1 - \frac{P_9}{I_9})R_4 + \frac{q_5}{C_5} + \alpha \frac{P_{12}}{I_{12}} \tag{2}$$

$$\dot{p}_{12} = \alpha(Sf_1 - \frac{P_9}{I_9}) - \frac{P_{12}}{I_{12}} R_{13} - \frac{q_{14}}{C_{14}} \tag{3}$$

$$\dot{q}_{14} = \frac{P_{12}}{I_{12}} \tag{4}$$

In the above state-space equations, q_5 and q_{14} are the generalized displacement variables; p_9 and p_{12} are the momentum variables. q_5 defines the relative displacement between the rigid frame (shown as MTS frame) and the mass (M). q_{14} represents the induced electrical charge in the voice coil-RLC circuit. p_9 defines mass momentum and p_{12} shows the flux linkage variable (λ) which is equal to time integral of the induced voltage in the voice coil.

By taking Laplace transform of Eqs. 1 to 4, the ratio of mass acceleration (a_{out}) over the input acceleration (a_{in}) is derived as Eq. 5:

$$\frac{\frac{\dot{p}_9(s)}{I_9}}{sX_{in}(s)} = \frac{a_{out}(s)}{a_{in}(s)} = \frac{(sC_5R_4+1)(I_{12}C_{14}s^2 + C_{14}R_{13}s+1) + s^2C_{14}C_5\alpha^2}{(I_9C_5s^2 + C_5R_4s+1)(I_{12}C_{14}s^2 + C_{14}R_{13}s+1) + s^2C_{14}C_5\alpha^2}$$

To simulate the design of Fig. 2 in MATLAB, the following parameters were chosen:

K_{sp}	Stiffness of the spring, (C_5=1/ K_{sp}), 509.94 N/m
R_{sp}	Damping of the spring, (R_4= R_{sp}), 17 N.s/m
$M+M_{coil}$	Disk Mass (M) plus Coil mass (I_9 = $M+M_{coil}$), 1.44+0.204=1.644 Kg
α	Voice coil force sensitivity ($GY_{10-11} = \alpha$), 21.1 N/Amp
I_{coil}	Voice Coil Inductance, 17.5 mH
I_v	Variable Inductance, $0 < I_v < 210$ mH
R_{coil}	Voice Coil Resistance, 9 ohms
R_v	Variable Resistance, $0 < R_v < 1000$ ohms
C_v	Shunted Capacitance (C_{14}), 0 < Cv <3300 μf

A parametric study was done to evaluate the effect of changing resistance, inductance and capacitance of the RLC circuit on $\frac{a_{out}(s)}{a_{in}(s)}$ ratio. The parametric study defines how the variation in the electrical components affects the natural frequency of the TVA, and which one is the most viable to use as a variable component to change TVA natural frequency. The following sections describe the simulation results.

EFFECT OF A VARIABLE RESISTANCE (R_V) ON NATURAL FREQUENCY OF THE ETVA

First, it is assumed that a variable resistance is connected to the coil. Therefore, the coil model plus the electrical circuit (Fig. 3) includes the coil resistance (R_{coil}), coil inductance (I_{coil}), and a variable resistance (R_v). In the bond graph model of Fig. 4, R_{13} represents the combination of the coil resistance plus the variable resistance (R_{coil+} R_v). I_{12} defines the coil inductance (I_{coil}) and C_{14} is assigned equal to 10e6 μf to eliminate the capacitance from the model.

Fig. 5 shows how changing shunted resistance affects the natural frequency of the ETVA. When the shunted resistance (R_v) varies from a very low value (short circuit voice coil) to a very high one (open circuit voice coil), the natural frequency of the ETVA and the peak value of (a_{out}/a_{in}) increase. According to the bond graph model of Fig. 4, when the shunted resistance (R_v) increases, the induced current ($i_{induced}$=flow in bond 11) in the coil-RLC circuit decreases; so the applied force (F= α * $i_{induced}$ = force in bond 10) from the voice coil to the SDOF mass-spring system decreases. Ultimately, when the shunted resistance goes to a very high value, the induced current goes to zero and no force will be applied from the voice coil to the mass (M). In this case, the whole system reduces to a SDOF mass spring system. So, the natural frequency of the ETVA approaches to the natural frequency of the SDOF system (2.8 Hz for the selected parameters).

On the contrary, when the coil's wires are short circuited with no shunted resistance (R_v), the induced current in the coil-RLC circuit will be high; therefore the applied force ($F = GY_{10\text{-}11} * i_{\text{induced}}$ = force in bond 10) from the voice coil to the mass (M) will be noticeable. This force tends to increase the apparent stiffness that the mass (M) sees, so the ETVA apparently becomes rigid and mass (M) motion follows the excited motion (a_{out}/a_{in} approximately 1). For the applications that the peak value of the (a_{out}/a_{in}) is going to be used; higher resistance can give higher (a_{out}/a_{in}) peak value.

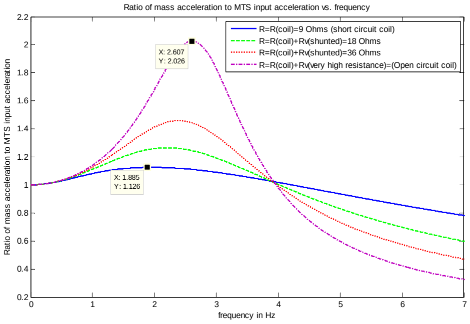

Figure 5. Ratio of mass acceleration to input acceleration (a_{out}/a_{in}) versus frequency (Variable resistance is shunted to the voice coil)

VOICE COIL WITH SUPERCONDUCTING WIRES

The simulation result of Fig. 5 was for an ETVA with the coil resistance (R_{coil}) of 9 Ohms. However, if the coil could be manufactured from a very low resistance wire such as a room temperature superconducting wire, the natural frequency of the ETVA would change in a very wide frequency range.

Fig. 6 shows that when the coil of ETVA is made of a very low resistance wire (1 Ohms or less), the natural frequency of the ETVA can be shifted by approximately 8 times from 19 Hz to 2.8 Hz when a variable resistor is shunted to the voice coil. According to the bond graph model of the ETVA (Fig. 4), when the coil resistance is very low and the coil's wires are short circuited, R_{13} can be considered negligible. So the only remaining element is an inductance (I_{12}), which is bonded to the gyrator ($GY_{10\text{-}11}$).

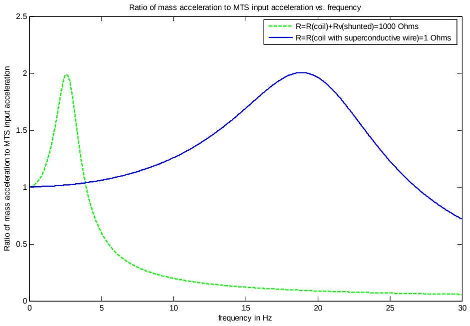

Figure 6. Ratio of mass acceleration to MTS input acceleration (a_{out}/a_{in}) versus frequency (for a very low resistance voice coil and a high resistance voice coil)

Based upon bond graph modeling technique [3], when an inductance (I) is bonded to a gyrator, it acts like a capacitance (C) which is equivalent to a compliance in a mechanical system (see Fig. 7).

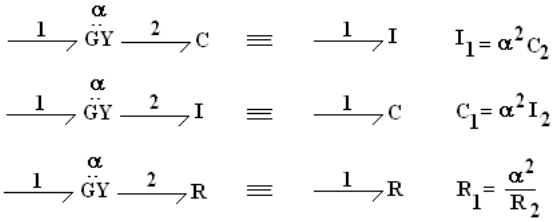

Figure 7. Bond graph principle [3]

Therefore when a low resistance coil is short circuited, in a sense, a compliance is added to the SDOF system; so, the total stiffness of the ETVA increases and in consequence the natural frequency of the ETVA goes up.

On the contrary, when a very high resistance is shunted to the voice coil, the induced current in the coil decreases and the contribution of voice coil to the mass-spring motion is negligible. So the total ETVA acts like a SDOF system and its natural frequency approaches to the natural frequency of the SDOF mass-spring system. Generally, for the applications where the change in the disturbance frequency is large, this type of ETVA would be quite useful.

Literature review indicates that room temperature superconducting wires will be commercially available within 5 to 10 years time. Once such a technology is available, the creation of an adaptive ETVA with a widely variable natural frequency would be possible.

EFFECT OF A SHUNTED VARIABLE INDUCTANCE (I_V) ON THE NATURAL FREQUENCY OF THE ETVA

Another parametric study was done on a shunted variable inductance. Here, the coil model plus the electrical circuit (Fig. 3) consists of the coil resistance (R_{coil}), coil inductance (I_{coil}) and a variable inductance (I_v). In the bond graph model of Fig. 4, I_{12} represents the coil inductance plus the variable inductance ($I_{coil}+I_v$), R_{13} shows the coil resistance, and C_{14} is set to a very high value, namely 10e6 μf , to eliminate the capacitance from the model.

Simulation result for the ETVA with the shunted variable inductance is shown in Fig.8. Changing inductance from 17.5 (mH) to 210 (mH) changes the natural frequency of the ETVA by 50%. According to the bond graph modeling principles [3], when an inductance (I) is bonded to a gyrator (GY), it acts like a capacitance (C) which is equivalent to a compliance in a mechanical system (see Fig. 7). Therefore, by varying the shunted inductance, the compliance of the ETVA varies and in consequence its natural frequency changes. However, it should be noted that an inductance has some inherent resistance and when the inductance is changed, the inherent resistance of the inductor is also varied simultaneously; so, the shunted inductance is not controllable independently from its resistance. Therefore, creating an adaptive ETVA using an inductance would not be a suitable choice.

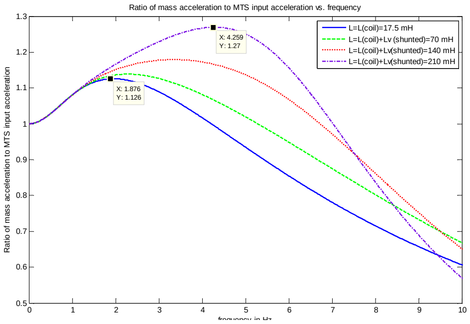

Figure 8. Ratio of mass acceleration to MTS input acceleration (aout/ain) versus frequency (Variable inductance)

EFFECT OF A SHUNTED VARIABLE CAPACITANCE (C) ON THE NATURAL FREQUENCY OF THE ETVA

The last parametric study was done by connecting a variable capacitance to the voice coil. The coil model plus the electrical circuit (Fig. 3) consists of the coil resistance (R_{coil}), coil inductance (I_{coil}) and a variable capacitance (C_v). In the bond graph model of Fig. 4, R_{13} represents the coil resistance (R_{coil}). I_{12} defines coil inductance (I_{coil}) and C_{14} represents the variable capacitance (C_v).

In the MATLAB simulations, the variable capacitance is varied from 0 (a very low capacitance) which is equivalent to an open circuit, to 1000 μf , 3300 μf and very high capacitance which is equivalent to a short circuit. Fig. 9 shows the ratio of the mass acceleration to the input acceleration (a_{out}/a_{in}) versus frequency as shunted capacitance is varied. So, when a capacitor (C) is connected to a Gyrator (GY), it plays the role of an inductor and it is equivalent to a mass in the mechanical system (See Fig. 7). Therefore, when the capacitance is varied, the apparent mass of the TVA is changed thus the natural frequency of the TVA. For the current selected parameters, when the shunted capacitance is varied from a very low value (≈ 0) to 3300 μf , natural frequency of the TVA changes by 66%, from 2.5 Hz to 1.5 Hz.

As is seen in Fig. 9, changing capacitance not only changes the natural frequency of the TVA but also the peak value of the (a_{out}/a_{in}) at the resonance frequency.

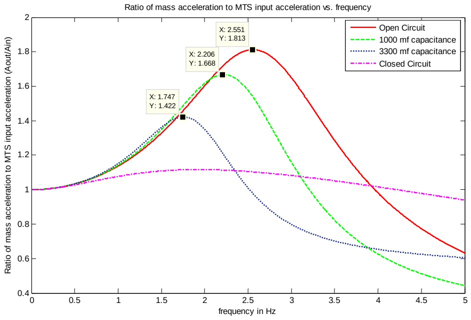

Figure 1. Ratio of mass acceleration to MTS input acceleration (a_{out}/a_{in}) versus frequency (Variable capacitance)

The peak value reduction occurs because of the coil resistance and the capacitance C_v. TVAs work most effectively when there is little damping present in the TVA. So, in order to have an adaptive ETVA with good performance, all damping and the coil resistance should be kept to a minimum.

To analytically show the location of the ETVA resonance frequency and resonance peak amplitude as a function of capacitance, the following steps are taken.

If the damping of the springs and resistance of the coil are kept very low, Eq. 5 reduces to,

$$\frac{\frac{\dot{p}_9(s)}{I_9}}{sX_{in}(s)} = \frac{a_{out}(s)}{a_{in}(s)} = \frac{(I_{12}C_{14} + C_{14}C_5\alpha^2)s^2 + 1}{(I_9C_5I_{12}C_{14})s^4 + (C_{14}C_5\alpha^2 + I_9C_5 + I_{12}C_{14})s^2 + 1} \quad (6)$$

The natural frequency of the ETVA is derived by taking derivative of Eq. 6 and setting it to zero,

$$\frac{d}{ds}\left(\frac{a_{out}(s)}{a_{in}(s)}\right) = 0 \Rightarrow \frac{d}{ds}\left(\frac{(I_{12}C_{14} + C_{14}C_5\alpha^2)s^2 + 1}{(I_9C_5I_{12}C_{14})s^4 + (C_{14}C_5\alpha^2 + I_9C_5 + I_{12}C_{14})s^2 + 1}\right) = 0$$

$$s^2 = \frac{-1 \pm \sqrt{(-C_5\alpha^2 / I_{12})}}{(I_{12}C_{14} + C_{14}C_5\alpha^2)} = \frac{1}{C_{14}}\frac{-1 \pm \sqrt{(-C_5\alpha^2 / I_{12})}}{(I_{12} + C_5\alpha^2)} \quad (8)$$

$$\left\| \frac{a_{out}(i\omega)}{a_{in}(i\omega)} \right\|_{\omega=resonance\ frequency} = (1 - \frac{I_9C_5}{I_{12}C_{14}}\left(1 + \sqrt{\frac{C_5\alpha^2}{I_{12}}}\right)^{-1})^{-1/2} \quad (9)$$

Eqs. 8 and 9 verify the MATLAB simulation results. Eqs. 8 and 9 show that increasing capacitance (C_{14}), not only decreases the natural frequency of the ETVA, but also the peak amplitdue of the (a_{out}/a_{in}) at the resonance frequency. It was mentioned earlier that damping and capacitance both impact the resonance peak amplitude, but it is important to mention that if the coil resistance is high, when capacitance is increased, the peak amplitude drops more aggressively than without any damping.

In summary, a comparison between Fig. 5, Fig. 8, and Fig. 9 shows that a variable capacitance is the most effective way of changing natural frequency of the TVA than changing resistance or inductance. Moreover, in comparison to other tunable TVA devices in the literature, this device provides more tunability in the natural frequency ($\approx 60\%$) than other methods. The parametric study and simulation results show that creating an adaptive ETVA using a variable capacitor would be the best viable choice. However, when room temperature superconductive wire technology is commercially available, a superconductive voice coil would create the best adaptive ETVA which is tunable in a larger frequency range.

EXPERIMENTAL VERIFICATION

To verify the above simulation results, an experimental test rig was developed. Here in section, the ability of a variable capacitance in creating an adaptive ETVA was examined and compared with simulation results. Similar experiment can be done for an ETVA with variable inductance and variable resistance.

As is shown in Fig.10, the designed apparatus consists of 4 axial stainless steel springs (K_{eq}=509 N/m, R_{eq}=20 N.s/m), a steel disk (M=1.44 Kg), a voice coil (M_{coil}=0.204 Kg, L=17.5 mH, R=9 Ohms, α =21.2 N/amp), and a circuit board consisting of various capacitors. A sinusoidal driving displacement is applied to the ETVA system using an MTS810 test machine. Two piezoelectric accelerometers are used, one attached to the steel disk and the other to the base plate of the test rig to measure the mass acceleration (a_{out}) and the MTS input acceleration (a_{in}); respectively. The capacitance which is shunted to the coil was varied, similar to the simulation, meaning from 0 which is equivalent to an open circuit to

1000 μf and then to 3300 μf which is equivalent to a short circuit. Practically, there are two possibilities for the variable capacitance circuit. Using commercially available variable capacitors or design a customized arrays of capacitors from the available constant capacitors on a circuit board which covers the required capacitance range. However, the size of capacitors in the array should be chosen such that a full range of tuning (from very low (open circuit) to high (short circuit) could be observed with a good accuracy. Here in this experiment an array of capacitors was put on a circuit board.

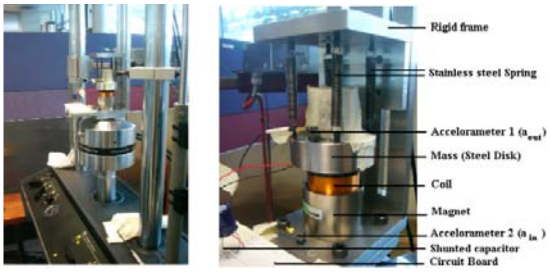

Figure 10. Experimental Test rig of ETVA

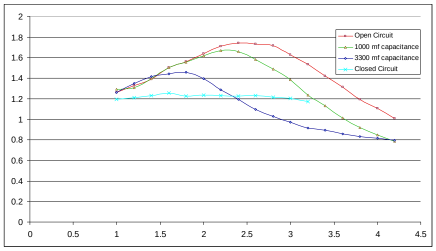

Figure 11. Experimental data for Ratio of mass acceleration to MTS input acceleration (a_{out}/a_{in}) versus frequency

Experimental results are plotted in Fig.11. A comparison between Figs. 9 and 11 reveals that the experimental data and theoretical simulation data are very similar. It verifies the viability of the proposed ETVA design. Similarly, ETVA with a variable inductance and a variable resistance can be fabricated and tested, but here in this paper those experiments are not shown.

Since the viability of the proposed ETVA is analytically and experimentally proven, the adaptive ETVA can now be used in conjunction with a passive hydraulic mount to create a semi-active hydraulic mount.

SINGLE PUMPER HYDRAULIC (FLUID) MOUNTS

Here in this section, a brief discussion on single pumper hydraulic (or fluid) mounts is given. Single pumper fluid mounts are widely used in the automotive and the aerospace applications [4]. A passive hydraulic or fluid mount, see Fig. 12, consists of a fluid contained in two elastomeric cavities (or fluid chambers) that are connected together through an inertia track. When a sinusoidal motion is applied to the fluid mount, the fluid will oscillate between the two fluid chambers. The oscillating fluid having mass, bounces between the two chamber volumetric stiffnesses and the vertical (or axial) stiffness, and eventually goes to resonance at a frequency called "notch frequency". At this frequency, the fluid mount dynamic stiffness decreases considerably and thus the transmitted force; therefore, providing cabin noise and vibration reduction. To place the "notch frequency" to any desired location, the fluid mount designer needs to use appropriate inertia track length, diameter, fluid density and viscosity, and rubber stiffnesses. Fig. 13 shows a typical dynamic stiffness of a passive fluid mount versus frequency.

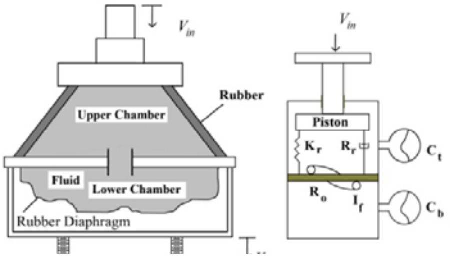

Figure 12. Passive Single Pumper Hydraulic Mounts

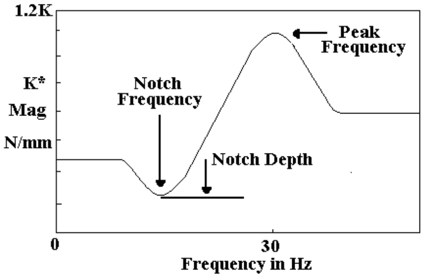

Figure 13. Dynamic Stiffness of a Typical Fluid Mount versus Frequency [4]

NEW SEMI-ACTIVE FLUID MOUNT DESIGN

Fig.14 shows the mathematical model of the new semi active hydraulic or fluid mount design where the lower chamber of a conventional single pumper fluid mount (Fig. 12) is replaced by the proposed ETVA system. Fig. 14 shows, in the bottom fluid chamber, a piston is supported by a spring. A fabric diaphragm (with high volumetric stiffness) is placed on the top of the piston, sealing the bottom fluid chamber. As fluid enters the bottom chamber, it moves the piston. When the piston moves, it moves the coil in and out of the permanent magnet. As coil moves up and down in the permanent magnet, current is generated in the coil's copper wire. The coil has N turns of pure copper wire. The coil's wire has some inductance and resistance, but a variable capacitance is also added to the coil's electrical circuit, for the purpose of varying natural frequency of the ETVA. With most fluid mount designs, great efforts are made to minimize flow losses and damping; so, here again ideally not only we would like to have very low inertia track flow losses, and rubber damping, but also we would like to have very small resistance in the coil wires and the entire electrical system. In this new design, volumetric stiffness of the bottom chamber is varied by varying the shunted capacitance thus the notch frequency of the fluid mount.

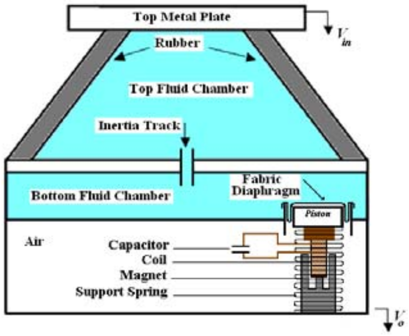

Figure 14. Variable Bottom Chamber Volumetric Stiffness Fluid Mount Design

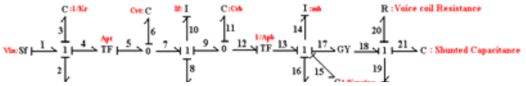

Figure 15. Bond graph Model of Fig. 14

In order to derive the constitutive equations of Fig. 14, its bond graph model was developed and it is shown in Fig. 15. From the bond graph model (Fig.15), the following state-space equations are derived:

$$\dot{q}_3 = V_{in} \tag{10}$$

$$\dot{q}_6 = A_p V_{in} - \frac{P_{10}}{I_{10}} \tag{11}$$

$$\dot{p}_{10} = \frac{q_6}{C_6} - R_8 \frac{P_{10}}{I_{10}} - \frac{q_{11}}{C_{11}} \tag{12}$$

$$\dot{q}_{11} = \frac{P_{10}}{I_{10}} - A_{pb} \frac{P_{14}}{I_{14}} \tag{13}$$

$$\dot{p}_{14} = A_{pb} \frac{q_{11}}{C_{11}} - \frac{q_{15}}{C_{15}} - R_{16} \frac{P_{14}}{I_{14}} - \alpha \frac{P_{19}}{I_{19}} \tag*{(14))}$$

$$\dot{q}_{15} = \frac{P_{14}}{I_{14}} \tag{15}$$

$$\dot{p}_{19} = \alpha \frac{P_{14}}{I_{14}} - R_{20} \frac{P_{19}}{I_{19}} - \frac{q_{21}}{C_{21}} \tag{16}$$

$$\dot{q}_{21} = \frac{P_{19}}{I_{19}} \tag{17}$$

In the above state-space equations, q_3, q_6, q_{11}, q_{15} and q_{21} are the generalized displacement variables; p_{10}, p_{14} and p_{19} are the momentum variables. The state-space variables are defined as:

q_3	Relative motion across the mount
q_6	Top chamber change in volume
q_{11}	Bottom chamber change in volume
q_{15}	Lower piston displacement
q_{21}	Induced electrical charge in the Voice coil-capacitor circuit
p_{10}	Time integral of the pressure drop in the inertia track (Pressure momentum)
p_{14}	Lower piston momentum
p_{19}	flux linkage variable (λ) (Time integral of induced voltage in the voice coil-capacitor circuit)

The input force (effort at bond 1) is equal to:

$$F_{in} = \frac{q_3}{C_3} + R_2 V_{in} + A_p \frac{q_6}{C_6} \tag{18}$$

To simulate the design of Fig. 14, MATLAB Program and the above State Space equations were used. The following parameters were used for the MATLAB simulation.

Table 2- Fluid Mount and ETVA Parameters Used in Matlab

$K'_r = 1/C3$	Real comp. of vertical stiffness, N/m	2.05e6
K''_r	Imag. comp. of vertical stiffness, N/m	0.0
A_p	Effective Piston area, m^2	0.009
A_t	Inertia track area, m^2	3.66e-4
A_m	Cross sectional area of the mass, m^2	6.45e-4
$I_f = I_{10}$	Inertia track fluid inertia, N-S^2/m^5	8.564e5
$R_o = R_8$	Inertia track flow resistance, N-S/m^5	6.4e6
$K_{vt} = 1/C_6$	Top Chamber Volume Stiffness, N/m^5	1.1e11
$K_{vb} = 1/C_{11}$	Compressibility of the fluid, N/m^5	2.1e14
$K = 1/C_{15}$	Stiffness of support spring K, N/m	8750
$M = I_{14}$	piston mass+ coil mass (kg)	0.771
$b = R_{16}$	Spring Damping, N.s/m	0.0
$R_{coil} = R_{20}$	Coil copper wire resistance, ohms	2.6
$I_{coil} = I_{19}$	Coil Inductance (mH)	2.9
$\alpha = GY_{17\text{-}18}$	Voice coil force sensitivity (N/amp)	35.14
$C_v = C_{21}$	Shunted Capacitance, μf	Varies

In the MATLAB simulations, the variable capacitance parameter, C_{21}, was varied from a very low value (open circuit) to 3300 μf. Fig. 16 shows the dynamic stiffness of the new fluid mount design versus frequency as the element C_{21} is varied. The simulation shows that the notch frequency moves about 12 Hz (more than 50 %) and generally it is enough for fine tuning of the notch frequency of a fluid mount.

Fig. 17 shows that as the mass I_{14} (coil+ piston) decreases, the notch frequency only moves 4 Hz while the shunted capacitance was kept at 1000 μf. This implies that the mass I_{14} should not be kept very low. However, for the aerospace applications which weight is an important issue, the coil and the piston mass should be selected such that the change in the capacitance gives the required frequency variation range while the mass of the mount is kept low.

Fig. 18 shows that as the coil resistance, R_{20} decreases, the notch will be deeper for the same variation in the capacitance. In order to get a deep notch, the coil resistance, R_{20}, should be kept as low as possible.

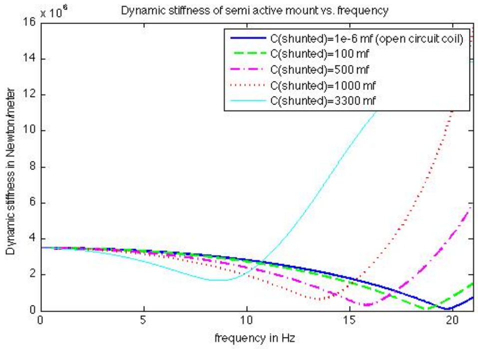

Figure 16. Dynamic Stiffness as variable capacitance parameter is varied from open circuit to 3300 μf

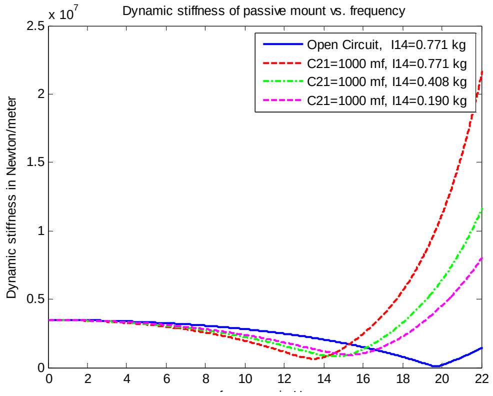

Figure 17. Dynamic Stiffness at different piston weight (C_{21} is equal to 1000 μf)

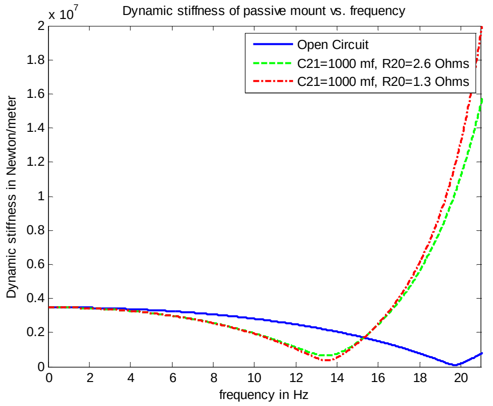

Figure 18. Dynamic Stiffness at different coil resistance (C21 is equal to 1000 μf)

CONCLUSIONS

An adaptive electromechanical tuned vibration absorber (ETVA) was introduced. It includes a voice coil, a single degree of freedom mass spring system and an electronic RLC circuit. The electronic circuit (RLC circuit) was added to the voice coil in series and it was used to tune the natural frequency of the ETVA. The mathematical model of the ETVA was defined and parametric studies were performed to evaluate the effect of variable resistance, variable inductance and variable capacitance in tuning the natural frequency of the ETVA. Parametric study showed that if the technology of room temperature superconductive wires is improved; using a voice coil made of superconductive wires plus a variable resistance would create the best adaptive ETVA which is tunable in a large frequency range (more than 900%). However among commercially available voice coils, it was shown that the variable capacitance is the most feasible approach to use at this point in time to vary the natural frequency of the ETVA. Natural frequency of the ETVA was varied by 66% when the shunted capacitance condition is varied from an open circuit to a short circuit.

The viability of the proposed ETVA design was verified by developing an experimental test rig. Comparison of the simulation results with the experimental data showed a remarkable correlation between the two. Experimental data revealed that a variable capacitance is able to change the natural frequency of the ETVA by 66%.

The application of ETVAs in creating a variable notch frequency fluid mount design was studied. Simulation results showed that indeed it is possible to vary the notch frequency location by 50% with the change of shunted capacitance of the ETVA. As the capacitance is changed, the effective volumetric stiffness of the bottom chamber changes; and so does the notch frequency.

When fluid mounts are manufactured, due to tolerances on all the fluid mount dimensions, material property variations, and variation in elastomer molding processes, the notch frequency never ends up at the right location on the 1st manufacturing pass. So with this new design, the notch frequency can be easily tuned to any desired location on the 1st manufacturing pass.

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