

Electromagnetic Shunt Damping

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Abstract

A method for electromagnetic shunt damping (EMSD) will be presented in this paper. Compared to piezoelectric shunt damping, the proposed EMSD vibration controller has a number of benefits. It requires small shunt voltages, can provide large stroke and can dampen larger mechanical structures. A passive control strategy is validated through experimentation on a simple electromagnetic mass-spring-damper system. Theoretical results are also presented.

1 Introduction

Electromagnetic transducers [1, 2, 3] can be used as actuators, sensors or both. When a current is applied to the terminals of the transducer a force is exerted and when a velocity is applied a voltage is induced across the terminals of the transducer. Piezoelectric transducers [4] exhibit similar electromechanical properties, but have considerably different physical characteristics to electromagnetic transducers. Electromagnetic transducers have a much greater stroke, typically in the millimeter range compared to the micrometer range associated with piezoelectric transducers. These devices are physically robust and can be manufactured to either MEMS scale [5], or as large as a $50kN$ electrodynamic shaker [6]. Electromagnetic transducers have been used in the field of active vibration control of car suspension systems [7], isolation platforms [8], magnetic levitation [9, 10] and magnetic bearings [11].

Placing an electrical impedance (or admittance) across the terminals of a piezoelectric transducer which is bonded to a resonant structure with the view to minimizing structural vibrations, is referred to as piezoelectric shunt damping [12, 13, 14, 15, 16]. This has been proven to be a reliable alternative to active control techniques [4, 17], offering the benefits of stability and performance without the need of additional sensors. Most importantly, the inherent robustness makes passive shunt control techniques very desirable. Another desirable characteristic is *collocation* [18]. Shunt damping, by its very nature, is collocated, therefore enhances the stability characteristics of the closed loop system.

This paper presents a new shunt method for reducing structural vibration; electromagnetic shunt damping (EMSD). By attaching an electromagnetic (or electrodynamic) transducer

to a resonant mechanical structure and shunting the transducer with an electrical impedance (or admittance), kinetic energy from the resonant structure can be dissipated. As the mechanical structure displaces, an opposing electro-motive force (emf) is induced in the transducer. This potential, and corresponding shunt current, results in the dissipation of energy in resistive circuit components. Using an appropriately designed electrical shunt the transducer is capable of significantly reducing mechanical vibration.

Compare to piezoelectric shunt damping, the EMSD offers large stroke, more robustness, smaller shunt voltages, and larger control forces.

2 Background

2.1 Electromagnetic Transducer Model

When an electrical conductor, in the form of a coil, moves in a magnetic field as shown in Figure 1 (a), a voltage V_e proportional to the velocity \dot{x}_e is induced and appears across the terminals of the coil, i.e. $V_e \propto \dot{x}_e$. Specifically,

$$\frac{V_e}{\dot{x}_e} = Dl, \quad (1)$$

where D is the magnetic flux (in Teslas), l is the length of the conductor (in meters), and \dot{x}_e is the velocity of the conductor relative to the magnetic field (in m/s). A permanent magnet is usually the source of the magnetic field.

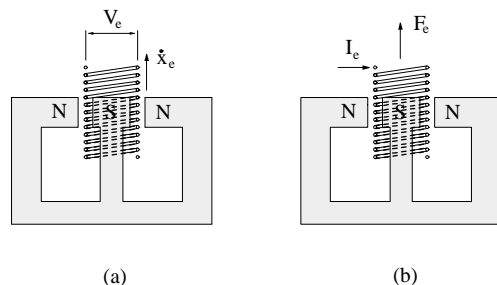


Figure 1: Electromagnetic transducer, (a) sensor and (b) actuator.

Equation (1) can ideally be rewritten as [2],

$$\frac{V_e}{\dot{x}_e} = \frac{F_e}{I_e} = Dl = C_n \quad (2)$$

where F_e denotes the force (in Newtons) acting on the coil whilst carrying a current I_e (in Amps), and C_n is the ideal electro-mechanical coupling coefficient. As shown in Figure 1 (b), when the coil is employed as a force actuator, Equation (2) relates the induced force to an applied current. Such designs form the basis for electrodynamic shakers and acoustic actuators, such as a speaker coil.

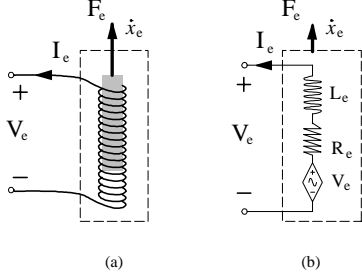


Figure 2: Electromagnetic transducer (a) mechanical model and (b) electrical model.

Equation (2) can be simplified with the assumption that the electromagnetic transducer operates in its linear region, i.e., undergoes only small displacements. As shown in Figure 2 (a), the coil can be modeled as series connection of an inductor L_e , a resistor R_e and a dependent voltage source V_e [3]. If the transducer is attached to a resonant mechanical system, the voltage source V_e , represents the induced emf that is dependent on relative velocity \dot{x}_e , and hence structural dynamics.

2.2 Forced Mass-Spring-Damper System

In many cases where vibration becomes an issue, the mechanical structure can be modeled as a simple mass-spring-damper system, as shown in Figure 3 (a). The equivalent mass M (in Kg), spring constant K (in N/m) and damping constant C (in Ns/m) for such a structure can be easily determined. The equation of motion for this forced one degree of freedom system is given by:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F_d(t), \quad (3)$$

where $\ddot{x}(t)$, $\dot{x}(t)$ and $x(t)$ are the acceleration, velocity and displacement of the mass respectively. Note that $F_d(t)$ is the applied force disturbance. The dimensionless representation of Equation (3) is

$$\ddot{x}(t) + 2\zeta_n\omega_n\dot{x}(t) + \omega_n^2x(t) = f_d(t), \quad (4)$$

where ω_n is the natural frequency of the system, and ζ_n is the damping ratio. Note that $\omega_n = \sqrt{\frac{K}{M}}$, $\zeta_n = \frac{C}{\sqrt{4MK}}$ and $f_d(t) = \frac{F_d(t)}{M}$.

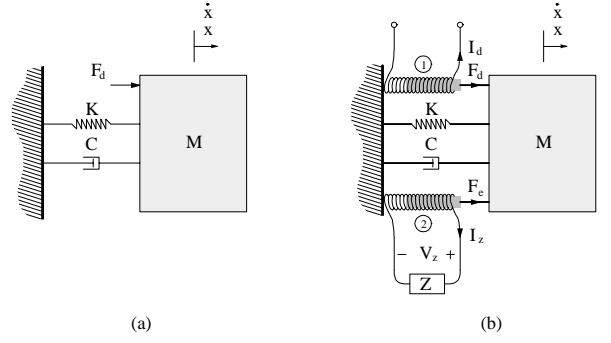


Figure 3: (a) Mass-spring-damper system and (b) electromagnetic shunted mass-spring-damper system.

3 Structural Dynamics from First Principles

3.1 Model System

Consider Figure 3 (b), where a electromagnetic transducer (coil 1) is attached to the mass. If a current $I_d(t)$ is applied to a linear electromagnetic transducer, a disturbance force $F_d(t)$ is induced such that, $F_d(t) = C_d I_d(t)$, where C_d is the electromagnetic coupling coefficient relating the applied current to a resulting force in coil 1. Using the equation of motion, the disturbed system has the following relationship, $M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = C_d I_d(t)$.

By taking the Laplace transform, the transfer functions relating the current $I_d(s)$ to displacement $x(s)$, and the current $I_d(s)$ to velocity $sx(s)$ are,

$$G_{xi}(s) \triangleq \frac{x(s)}{I_d(s)} = \frac{C_d}{Ms^2 + Cs + K}, \quad (5)$$

$$G_{\dot{x}i}(s) \triangleq \frac{sx(s)}{I_d(s)} = \frac{C_d s}{Ms^2 + Cs + K}. \quad (6)$$

These equations are valid when coil 2, is held in open circuit, i.e. $Z(s) = \infty$, as shown in Figure 3 (b).

3.2 Composite System

For an electromagnetic shunted composite system, as shown in Figure 3 (b), an impedance Z is attached to coil 2. we have the following relationship, $M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F_d(t) - F_e(t)$, where $F_e(t)$ is the opposing force due to the impedance Z attached to the terminals of the electromagnetic transducer. In the Laplace domain, we have the following relationship,

$$x(s)(Ms^2 + Cs + K) = C_d I_d(s) - F_e(s), \quad (7)$$

where $I_d(s)$ is the input current applied to coil 1, as shown in Section 3.1.

To determine the opposing force $F_e(s)$, we need to consider the simplified electrical model of the electromagnetic shunt, as shown in Figure 4. Ohm's law states that

$$V_z(s) = I_z(s)Z(s), \quad (8)$$

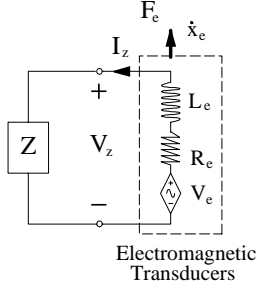


Figure 4: Simplified model of the electromagnetic shunt.

where $V_z(s)$ is the voltage across the terminals of the shunt impedance $Z(s)$, and $I_z(s)$ is the corresponding current. From the KVL, we obtain the following relationship between $V_e(s)$ and $V_z(s)$, as $V_z(s) = V_e(s) - (L_e s + R_e)I_z(s)$ which implies

$$V_z(s) = \frac{Z(s)}{L_e s + R_e + Z(s)} V_e(s). \quad (9)$$

As shown in Equation (1), we have the following linear relationship

$$V_e(s) = C_e s x(s), \quad (10)$$

where C_e is the electromagnetic constant relating $s x_e(s)$ to $V_e(s)$. Since the shunted electromagnetic transducer is attached to the mass M , $s x_e(s)$ is equivalent to $s x(s)$.

By substituting, (10) into (9), we obtain

$$V_z(s) = \frac{Z(s)}{L_e s + R_e + Z(s)} C_e s x(s). \quad (11)$$

Alternatively, the current flowing through the shunt $I_z(s)$, is

$$I_z(s) = \frac{V_z(s)}{Z(s)} = \frac{1}{L_e s + R_e + Z(s)} C_e s x(s), \quad (12)$$

and the opposing shunt force $F_e(s) = C_e I_z(s)$, assuming a linear electromagnetic transducer, we obtain

$$F_e(s) = C_e^2 \frac{1}{L_e s + R_e + Z(s)} s x(s) = C_e^2 \hat{K}(s) s x(s). \quad (13)$$

where $\hat{K}(s) = \frac{1}{L_e s + R_e + Z(s)}$.

Substituting (13) into (7), the composite system transfer function $I_d(s)$ to $x(s)$, is

$$\hat{G}_{xi}(s) \triangleq \frac{x(s)}{I_d(s)} = \frac{C_d}{M s^2 + (C + C_e^2 \hat{K}(s)) s + K}, \quad (14)$$

or alternatively, the transfer function relating $I_d(s)$ to $s x(s)$, is

$$\hat{G}_{xi}(s) \triangleq \frac{s x(s)}{I_d(s)} = \frac{C_d s}{M s^2 + (C + C_e^2 \hat{K}(s)) s + K}. \quad (15)$$

4 Composite System in Transfer Function Form

By modeling the system in transfer function form, we gain a greater abstraction from the underlying system. Such methods are particularly useful when dealing with higher order systems or when using models not obtained directly through physical modeling, i.e., when using models obtained by means of system identification [19]. Referring to Figure 5, the models required are: $G_{\dot{x}F}(s)$, the transfer function from an applied force to the resulting velocity \dot{x} ; and $G_{vi}(s)$, the transfer function from an applied current to the induced emf.

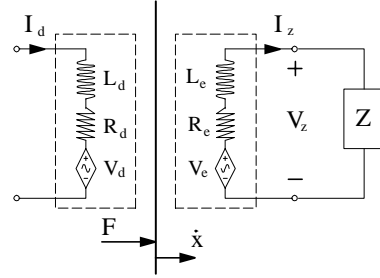


Figure 5: Electrical equivalent model of a twin coil electromagnetic system.

Considering first the case where two identical coils experience the same velocity. When an impedance $Z(s)$ is attached to coil 2, $V_z(s) = V_e(s) - (L_e s + R_e)I_z(s)$,

$$V_z(s) = \frac{Z(s)}{L_e s + R_e + Z(s)} V_e(s), \quad (16)$$

$$I_z(s) = \frac{1}{L_e s + R_e + Z(s)} V_e(s). \quad (17)$$

By considering the emf induced in both coils 1 and 2, and applying the principle of superposition, $V_e(s) = G_{vi}(s)I_d(s) - G_{vi}(s)I_z(s)$. Substituting (17) yields, $V_e(s) = G_{vi}(s)I_d(s) - G_{vi}(s)\frac{V_e(s)}{L_e s + R_e + Z(s)}$. Hence, the composite transfer function relating $I_d(s)$ to $V_e(s)$ is

$$\tilde{G}_{vi}(s) \triangleq \frac{V_e(s)}{I_d(s)} = \frac{G_{vi}(s)}{1 + \tilde{K}(s)G_{vi}(s)}, \quad (18)$$

where $\tilde{K}(s) = \frac{1}{L_e s + R_e + Z(s)}$. The reader will appreciate that the damped system transfer function $\tilde{G}_{vi}(s)$ is in the form of a feedback system where the impedance $Z(s)$ parameterizes a controller $\tilde{K}(s)$, as shown in Figure 6 (a).

The open loop transfer function $G_{vi}(s)$ consists of both the structural dynamics and the electromagnetic coupling, $G_{vi}(s) = C_e G_{xi}(s) = C_e^2 G_{\dot{x}F}(s)$.

In a more general case, we wish to know the damped transfer function $\tilde{G}_{\dot{x}F}(s)$ from some disturbance force $F(s)$ to the resulting velocity $s x(s)$. This is easily found,

$$\tilde{G}_{\dot{x}i}(s) \triangleq \frac{s x(s)}{I_d(s)} = \frac{V_e(s)}{I_d(s)} \frac{s x(s)}{V_e(s)}$$

$$= \tilde{G}_{vi}(s) \frac{sx(s)}{V_e(s)} = \frac{G_{\dot{x}i}(s)}{1 + \tilde{K}(s)G_{vi}(s)}. \quad (19)$$

Thus, $\tilde{G}_{xF}(s) \triangleq \frac{sx(s)}{F(s)} = \frac{sx(s)}{C_e I_d(s)} = \frac{1}{C_e} \tilde{G}_{\dot{x}i}(s)$, and

$$sx(s) = \frac{G_{\dot{x}i}(s)}{1 + \tilde{K}(s)G_{vi}(s)} I_d(s) + \frac{G_{xF}(s)}{1 + \tilde{K}(s)G_{vi}(s)} F(s), \quad (20)$$

as shown in Figure 6 (b). If coils are not identical, where $G_{vi}(s)$ is transfer function from the current in coil 2 to the induced emf, and $G_{\dot{x}i}(s)$ is the transfer function from the current in coil 1 to the velocity.

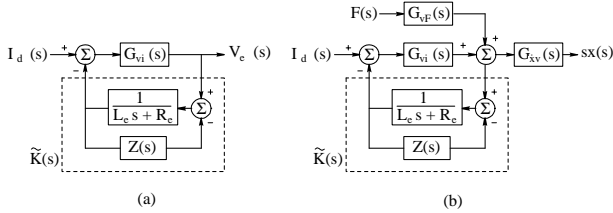


Figure 6: Electromagnetic shunt damping feedback structure: (a) Equation (18) and (b) Equation (20).

5 Single Mode Electromagnetic Shunt Controller

When a piezoelectric transducer is shunted by a passive electrical network, it acts as a medium for dissipating mechanical energy of the attached structure. Hagood and von Flotow [13] suggested that a series resistor-inductor circuit attached across the conducting surfaces of a piezoelectric transducer can be tuned to dissipate mechanical energy of a host structure. They demonstrated the effectiveness of this technique by tuning the resulting resistor-inductor ($R-L$) and inherit capacitance of the piezoelectric transducer, to a specific resonance frequency of the host structure.

For electromagnetic shunt damping, we can apply the same methodology as suggested above. For this particular system, though, we need to apply a resistor-capacitor ($R-C$) circuit to the terminals of the electromagnetic transducer. That is, $Z(s) = \frac{1}{C_{ap}s} + R$, where $C_{ap} = \frac{1}{\omega_n^2 L_e}$. Therefore, the shunted electromagnetic transducer $sx(s)$ is related to F_e via $F_e(s) = C_e^2 K_{ap}(s) sx(s)$, where $K_{ap}(s) = \frac{1}{L_e} \frac{1}{s^2 + \frac{R_t}{L_e}s + \frac{1}{C_{ap}L_e}}$. It should be noted that the controller has a resonant structure, where $R_t = (R_e + R)$ determines the controller damping and ω_n is the resonance frequency of the mechanical structure to be damped.

The closed loop composite transfer function between current-to-velocity is $\tilde{G}_{\dot{x}i}(s) \triangleq \frac{sx(s)}{I_d(s)} = \frac{C_d s}{Ms^2 + (C + C_e^2 K_{ap}(s))s + K}$ or alternatively, $\tilde{G}_{\dot{x}i}(s) \triangleq \frac{sx(s)}{I_d(s)} = \frac{G_{\dot{x}i}(s)}{1 + K_{ap}(s)G_{vi}(s)}$.

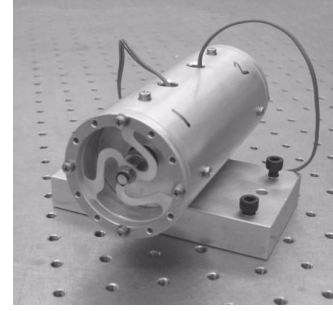


Figure 7: An external photograph of the experimental electromagnetic apparatus.

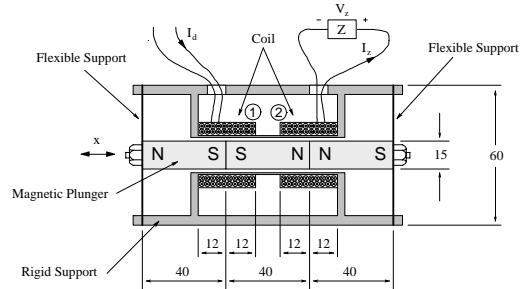


Figure 8: Side section of the experimental electromagnetic apparatus. (All dimensions in mm)

6 Experimental Verification of Electromagnetic Shunt Damping Concept

6.1 Electromagnetic Transducer Design

In support of the preceding sections, the technique of electromagnetic shunt damping was applied to an experimental assembly at the Laboratory for Dynamics and Control of Smart Structures in The University of Newcastle, Australia¹. A photograph of the electromagnetic transducer apparatus, showing the rigid external support, flexible end supports, mounting plate, coils and winding cables is provided in Figure 7. As shown in Figure 8, the assembly is essentially a translational solenoid with two identical fixed coils and a magnetic plunger supported at either end by flexible supports. This system is mechanically equivalent to the mass-spring-damper shown in Figure 3. Together with an attached electrical impedance $Z(s) = \frac{1}{C_{ap}s} + R$, coil 2 is employed to damp translational vibrations resulting from an applied disturbance current I_d to coil 1.

In practice, the magnetic field strength, as well as being a function of the magnetic material, is limited by the maximum allowable dimensions and weight of the magnets. In these experiments, three rare earth magnets (Neodymium Iron Boron), are arranged to form the magnetic plunger, as

¹<http://rumi.newcastle.edu.au/>

shown in Figure 8. At the two points where opposing poles meet (at the center of each winding), a strong magnetic field exits at right angles to the plunger. When the plunger is in motion, the strong parallel field flowing through the coil results in a high flux density and corresponding large induced force.

Each coil is wound from 0.25 mm diameter enamel coated copper wire and has an electrical impedance of 3.3 Ω and 1 mH. Non-magnetic materials, such as aluminum and copper, were used in the construction of the rigid external support, flexible end supports and the mounting plate. Non-magnetic materials were utilized so as to prevent the magnetic disturbance.

Parameter	Value
Spring constant K	56 kNm ⁻¹
Damping coefficient C	2.667 Nsm ⁻¹
Plunger mass M	0.150 kg
Electromagnetic Coupling C_d	3.65
Electromagnetic Coupling C_e	3.4
Coil Inductance L_e	1 mH
Coil Resistance R_e	3.3 Ω

Table 1: Electromechanical system parameters.

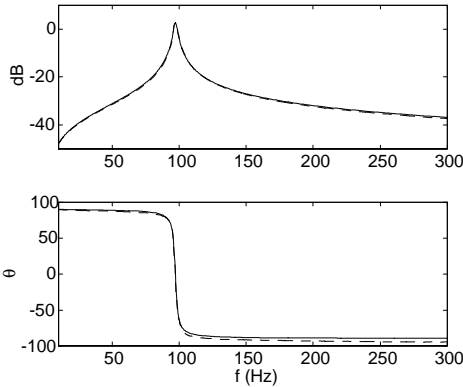


Figure 9: The open loop frequency response from an applied actuator current to plunger velocity, i.e. $G_{\dot{x}i}(s)$, model (-) and measured results (- -).

6.2 Determining Optimal Damping Resistance

The electromechanical model $G_{\dot{x}i}(s)$ was first determined by measuring the resonance frequency and plunger weight M , and subsequently the spring constant K . The remaining parameter ω_n , together with the electromagnetic coupling coefficients C_d and C_e , were determined experimentally. A summary of the model parameters is provided in Table 1. The frequency response from an applied current to the resulting plunger velocity $G_{\dot{x}i}(s)$, is shown in Figure 9. It is observed that the model is an accurate representation of the physical system.

Since we wish to damp the fundamental frequency of the

mass-spring-damper system, i.e. $\omega_n = 97.3$ Hz, the required shunt capacitance value is $C_{ap} = 2.6$ mF.

In order to determine an appropriate value for the total shunt resistance R_t , an optimization approach was used to minimize the \mathcal{H}_2 norm of the closed loop system $\tilde{G}_{\dot{x}i}(s)$. This required a solution to the following optimization problem to be found $R_t^* = \arg \min_{R_t > 0} \left\| \tilde{G}_{\dot{x}i}(s) \right\|_2$.

Using the proposed optimization strategy the required optimal shunt resistance $R_t^* = 0.29$ Ω , and alternatively R_t^* can be found by plotting \mathcal{H}_2 norm against R_t , as shown in Figure 10.

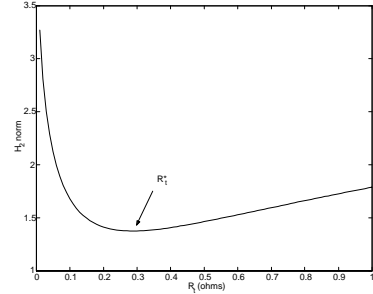


Figure 10: $\left\| \tilde{G}_{\dot{x}i}(s) \right\|_2$ against R_t (Ω).

6.3 Impedance Implementation

To implement the proposed arbitrary shunt impedance $Z(s)$, a current controlled voltage source was utilized, as shown in Figure 11. The controlled voltage v_z was set to be a function of the measured current i_z , i.e., $v_z(t) = f(i_z(t))$, as shown in Figure 11 (a). If the function $f(i_z(t))$, is a linear transfer function $Z(s)$ whose input impedance is the measured current $I_z(s)$, i.e., $V_z(s) = Z(s)I_z(s)$, then the terminal impedance $Z_t(s)$ is equal to $Z(s)$, as shown in Figure 11 (b). For a more detailed description of the impedance apparatus, the reader is referred to Fleming *et. al.* [20, 21].

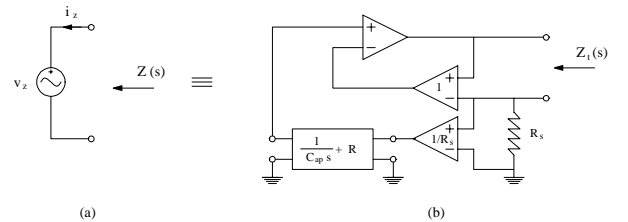


Figure 11: (a) Ideal current controlled voltage source, and (b) experimental current controlled voltage source.

6.4 Simulated vs Experimental Results

With the aim of damping the mechanical system, a total series resistance R_t of 0.35 Ω and a capacitor of 2.7 mF were applied to the second winding using the synthetic impedance apparatus explained in Section 6.3. The measured open loop, theoretically predicted damped, and measured damped

frequency responses are shown in Figure 12. A significant reduction of 21.8 dB in the magnitude of the electromechanical system can be observed.

Simulated and experimental results closely agree, therefore validating the proposed electromagnetic shunt damping.

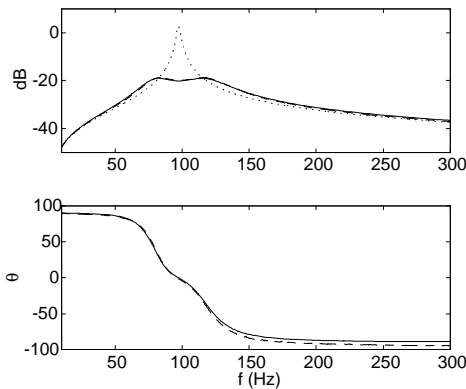


Figure 12: The open loop (\cdots), theoretically predicted damped ($-$), and measured damped ($- -$) frequency responses from an applied current to the resulting plunger velocity.

7 Acknowledgments

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