Negative Inductor-Resistor Controller for Electromagnetic Shunt Damping

S. Behrens, A.J. Fleming and S.O.R. Moheimani.

Abstract: One approach to vibration control involves shunting an electromagnetic transducer by an electrical impedance to dampen vibration of a mechanical structure. This letter presents a method for designing a novel shunt impedance: the negative inductor-resistor controller. Experimental validation is performed on a simple electromagnetic mass-spring-damper system.

Introduction: Mechanical structures are subject to vibrations that can diminish structural life, or in the worst case, contribute to mechanical failure. Due to the highly resonant nature of these structures, a disturbance, if occurred at a resonance frequency, may cause catastrophic failure.

Electromagnetic (or electrodynamic) transducers can be used as actuators, sensors, or both. By attaching an electromagnetic transducer to a resonant mechanical structure and shunting the transducer with an electrical impedance (or admittance), an opposing electro-motive-force (emf) is induced in the transducer, resulting in mechanical damping.

This letter will attempt to develop a simple broadband shunt controller by using some of the fundamental properties of the electromagnetic transducers.

Background: An ideal electromagnetic transducer, as shown in Fig. 1, satisfies the following relationship, $\frac{V_e}{\nu_e} = \frac{F_e}{I_e} = C_i$, where V_e is the induced voltage, proportional to the velocity ν_e, that appears across the terminals of the transducer. F_e denotes the force acting on the coil whilst carrying a current I_e and C_i is the ideal electro-mechanical coupling coefficient.

As shown in Fig. 1, an electromagnetic transducer coil can be modeled as the series connection of an inductor L_e, a resistor R_e and a dependent voltage source V_e. If the transducer is attached to a resonant mechanical structure, the voltage source V_e represents the induced emf that is dependent on relative velocity ν_e, and hence structural dynamics.

Using Ohm's law, KVL and the principle of superposition, we obtain the following relationship between the measured velocity $\nu_e(s)$ to the force $F_e(s)$ generated by the shunted electromagnetic transducer, $F_e(s) = \frac{C_e^2}{Z(s)+L_e s+R_e}\nu_e(s)$ [1]. Note C_e is the electro-mechanical constant for the shunted electromagnetic transducer.

Developing the Negative Inductor-Resistor Controller: Assuming a resonant structure, a simple electromagnetic mass-spring-damper system as shown in Fig. 1, the composite system transfer function relating $I_d(s)$ to $\nu(s)$, is

$$\frac{\nu(s)}{I_d(s)} = \frac{C_d s}{Ms^2 + \left(C + \frac{C_e^2}{Z(s)+L_e s+R_e}\right)s + K},$$

where M, K and C represents the mass, spring constant, and damping constant respectively [1]. $\nu(s)$ is the velocity of the mass M and $F_d(s) = C_d I_d(s)$, where $I_d(s)$ is the applied current disturbance and C_d is a electro-mechanical constant.

Assuming we want infinite damping of the mechanical structure, i.e. $\left(C + \frac{C_e^2}{Z(s)+L_e s+R_e}\right) = \infty$, the ideal shunt circuit network should consist only of the negative inductor and resistor, that is, $Z_{ideal}(s) = -(L_e s + R_e)$. This is not a realizable network as it creates an undamped resonance when attached to the electromagnetic transducer. Instead, we implement $Z(s) = -\varepsilon(L_e s + R_e)$, where ε is some gain $\varepsilon < 1$.

Implementation of the Negative Inductor-Resistor Controller: There are two possible ways to implement the proposed negative inductor-resistor controller: (a) negative impedance converter (NIC) [2] or (b) voltage-controlled-current-source (VCCS) [1, 3], as shown in Fig. 2.

In this letter, we employ the VCCS which is defined as a two terminal device that establishes some arbitrary relationship between voltage and current at its terminals i.e., $I_z(s) = \frac{V_z(s)}{Z(s)} = V_z(s)Y(s)$. For experimental purposes, a digital signal processor (DSP) system *dSPACE*[1] was used to implement the required function $Y(s)$ in real time.

Application: To support the preceding sections, a simple electromagnetic mass-spring-damper experimental apparatus was used [1]. Schematics of this system are shown in Fig. 3. The assembly is essentially a translational solenoid with two identical fixed coils and a magnetic plunger supported at each end by flexible supports. Experimental apparatus parameters are $M = 0.15Kg$, $C = 2.677Nsm^{-1}$, $K = 56kNm^{-1}$, $C_e = 3.4$, $C_d = 3.65$, $L_e = 1mH$ and $R_e = 3.3\Omega$.

Together with the proposed electrical admittance $Y(s) = \frac{-1}{\varepsilon(L_e s + R_e)}$ where $\varepsilon = 0.94$, as synthesized by VCCS, coil 2 is employed to damp translational vibrations resulting from an applied disturbance current I_d to coil 1. To remove discrepancies in C_e at high frequencies, the experimental admittance is low-pass filtered at $\approx 1kHz$, i.e. $Y(s) = \frac{-1}{0.94(L_e s + R_e)} \frac{1}{0.16s+1}$.

Open-loop and closed-loop responses are compared in Figure 4. It can be observed that the fundamental mechanical resonance is heavily damped, approximately $28dB$.

Conclusions: In this letter, we have introduced a new type of electromagnetic shunt impedance. The proposed negative inductor-resistor controller was experimentally validated on a simple electromagnetic mass-spring-damper system.

[1] dSPACE is a rapid prototyping digital signal processor system.

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References

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Figure Captions

Fig. 1: Electromagnetic shunted mass-spring-damper system.

Fig. 2: Implementation of negative impedance-resistor controller using a voltage-control-current-source (VCCS), where R_s is a sensing resistor.

Fig. 3: Experimental electromagnetic shunted mass-spring-damper apparatus. Note all dimensions are in millimeters (mm).

Fig. 4: Experimental results $\nu(s)/I_d(s)$: open-loop ($\cdots$) and closed-loop (—).

Figures

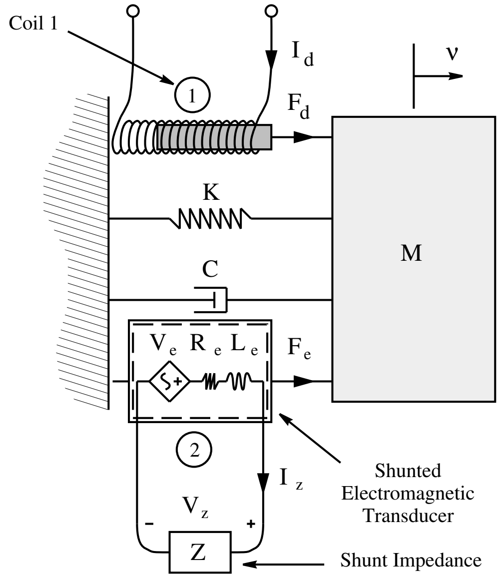


Figure 1:

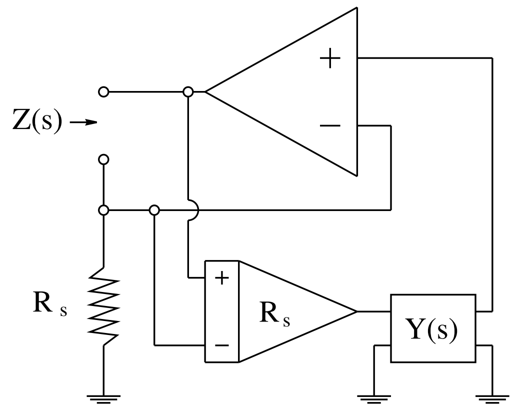
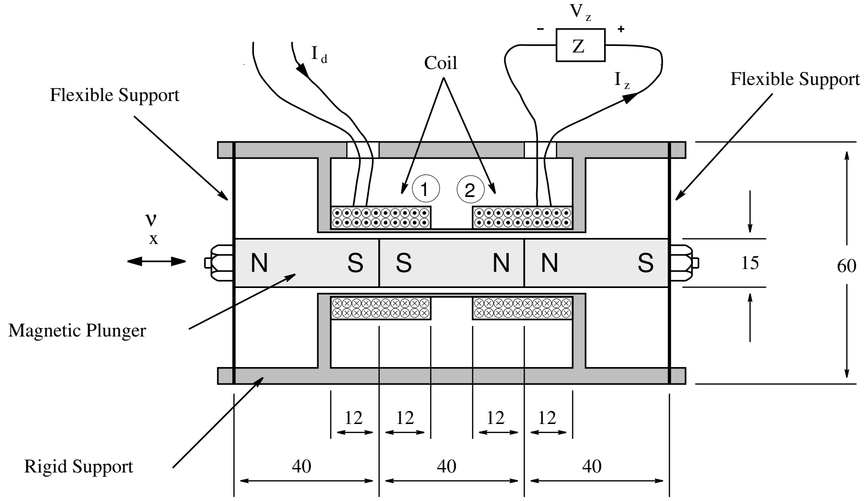
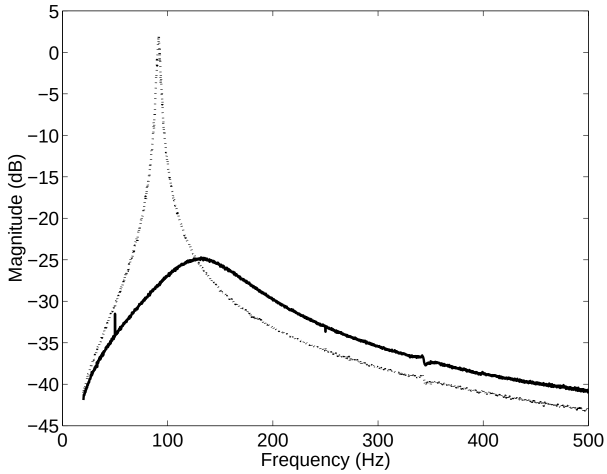


Figure 2:



V z
Z
- +
I d
Coil
I z
Flexible Support
Flexible Support
ν x
1
2
N S S N N S
15
60
Magnetic Plunger
Rigid Support
12 12 12 12
40 40 40

Figure 3:



Magnitude (dB)
Frequency (Hz)
5
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
0
100
200
300
400
500

Figure 4: