Design, simulation and experimentation of an electro-dynamic system for semi-active control of vibrations

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Abstract. Previous work regarding the vibration transmissibility control, using electrodynamic actuators, based on semi-active solutions, proved the efficiency of this strategy. The studied system is a simple, one degree of freedom system. The system integrates mechanical components for passive isolation and an electrodynamic actuator for active and semi-active control of vibrations. The most efficient solution is to design an accurate model and simulate strategies on it. Two strategies are involved: feed-forward control with an accelerometer placed on the mobile mass for acceleration detection and the second one is based on movement detection using the self-induced current due to the actuator's coil movement in a magnetic field. A detailed simulation model, using a software designed for electronic circuit simulation and experimental testing are performed in both cases. The model should be improved for considering the complex impedance of the actuator (mechanically but also electrically), this being the subject of future works.

1. Introduction
In most cases we try to find purely mechanical solutions because they are cheaper and easier to make. However, in some more demanding applications, mechanical solutions are not enough. In other words, springs and shock absorbers are replaced with actuators that, together with sensors and control systems, emulate the behaviour of mechanical systems. The main disadvantage of mechanical systems is that their parameters cannot be modulated during live operation. Within semi-active control systems, dynamic parameters can be very easily modulated either by an operator or by an automatic adjustment system. [1], [2]. Changing the dynamic behaviour of the semi-active vibration control system is indispensable in the case of a vibration environment with a random character. The implementations of the two basic principles were made with simple control systems and modest components that are available on the market. Previous work regarding the vibration transmissibility control using electrodynamic actuators, and semi-active solutions, proved the efficiency of this strategy [3], [4]. The research is intended to highlight two basic principles for semi-active vibration control. The main purpose is to reduce as much as possible the vibration’s amplitude generated either from the environment or from certain mechanical devices near vibration-sensitive systems. The practical implementation involves knowledge from several basic areas: vibration control, mechanical systems, electronics, computer science, system dynamics, control systems, etc. The studied system on Figure 1 is a simple mechanical system, with one degree of freedom, designed to isolate a body of mass "m" from external vibrations. The system integrates mechanical components for passive isolation (a
spring that has the elastic constant $k$ and a viscous damper with viscous damping constant $c$), and an electrodynamic actuator for active and semi-active control of the system. The electrodynamic actuator can develop an electrodynamic force $F_{ed}$ on the mechanical elements of the system. The actuator's terminals, can be connected to an external electric impedance $Z_e$. The electrodynamic actuator is the active element that is used to control the system's characteristics or it can be considered as a semi-active part of the same system when is used as a converter of mechanical energy into electrical energy that can be dissipated later by an external impedance ($Z_e$).

![Figure 1. The system model.](image)

2. Semi-active control of vibrations using an accelerometer and feed-forward principle

As can be seen in the block diagram of the system on Figure 2, the control system consists of few elements: accelerometers, power supply, signal generator, preamplifier with phase shift, power amplifiers and the mechanical parts. The signal generator is set to generate a sinusoidal signal with a frequency between 5 and 50Hz.

![Figure 2. The block diagram of the feed-forward system.](image)

The vibration of the electrodynamic exciter is detected using an accelerometer. Due to the use of an accelerometer, the amplitude of the output signal is frequency dependent. For this reason, the overall amplification of the feed-forward circuit must be changed as the frequency changes for optimal results. Also, due to the overall inertia of the system, the phase shift must be corrected accordingly. The experimental tuning of the system is done as follows: after
choosing an oscillation frequency and adjusting the amplitude so that a visible oscillation of the end part (loudspeaker membrane) is obtained, the amplification is set to minimum and the phase shift to zero, the power supply is turned on and then the amplification is increased until a reduction in amplitude is visibly observed on the analyser or oscilloscope. Large amplification is avoided in order to maintain a stability headroom. Finally, the phase shift is adjusted in both directions (phase advance and phase delay) until the amplitude of the vibration of the final element is reduced. Using the Proteus ISIS, a simulation diagram was created. Figure 3 is featuring the preamplification and phase advance / delay circuit and the power amplifier for the actuator. The power supply is modelled with two ideal batteries that are series connected to obtain a differential power supply. To simulate the signal from the accelerometer, a sinusoidal function generator is used, which is set to a frequency of 20Hz and the peak amplitude of 0.5V. The resistor R3 sets the input impedance and if the input is disconnected, this resistor keeps the input at a potential very close to the ground potential. A low-pass filter is used for noise attenuation using the resistor R4 and the capacitor C3. The filtered signal is then applied to a buffer (U1: A) via the protection resistor R5.

In this simulation, only the first operational amplifier (U1: A) is powered. The simulation program automatically powers the other amplifiers because they are part of the same integrated circuit (LM324). The signal from the buffer is applied to an inverting amplifier (U1: B) which is used for two main purposes: phase reversal and input signal preamplification. The potentiometer RV1 is used to adjust the preamplification (in the simulation diagram, the voltage gain can be increased if the cursor is moved to the left). The resistor R7 sets the maximum amplification (approximately -1000) and the resistor R6 maintains the non-inverting input at the ground potential, providing protection at the same time. The next circuit can induce either a phase advance or a phase delay. An upward movement of the RV2 potentiometer cursor will create a phase advance. The obtained signal is applied to a buffer and finally to the power amplifier (U2) after a low-pass filter (R13, C10). The potentiometer RV3 is used to adjust the voltage amplification. For the electrodynamic actuator modelling, R17 and L1 with the real values are used, having the dominant impedance.
Figure 4. Feed-forward circuit response - phase advance at 20Hz: blue - input signal; red - output signal.

Figure 5. Feed-forward circuit response - phase delay at 20Hz: blue - input signal; red - output signal.

3. Semi-active control of vibrations using the negative impedance principle
In the case of this semi-active mode of vibration control, the current through the electrodynamic actuator is permanently monitored with the help of a current to voltage converter (Figure 6). The resulting voltage is applied to an amplification and differentiation circuit. In the end, an inverting summing amplifier is used to mix three signals: the signal from the proportional factor (P), the signal from the derivative factor (D) and the signal from the auxiliary input (optional signal). In other words, this circuit is producing a current that is opposing of the induced current due to the vibration generated by the exciter.
In this case, the first accelerometer is connected to the signal analyser/oscilloscope for proper analysis. There are three modes of operation. The first one is high impedance mode. The purpose of this mode is to perform a "before and after" comparison. The amplitude from the accelerometer that is mounted on the end part is measured and recorded. The second mode with zero amplification and differentiation sets a low impedance, effectively shorting the actuator's coil, (the output impedance of the power amplifier for the electrodynamic actuator is almost zero). Because of this, the amplitude value is smaller. In this case, the actuator is acting like a dissipative element. In the third mode, the amplification is gradually increased until a minimum amplitude of the vibration of the final element is obtained. At higher frequency, the amplitude will begin to increase. This is due to the parasitic inductance of the actuator. In order to reduce the effect of this parasitic inductance, the amplitude of the derivative circuit is gradually increased until to a considerable reduction of the amplitude is obtained. The diagram on Figure 7 is powered in the same manner.

The current to voltage converter is using the resistor R18 as a shunt resistor. The voltage drop on the resistor is applied to the non-inverting amplifier with a gain of 10. From this circuit a 1V / 1A is obtained. The output signal is then applied to two potentiometers for weight adjustment (proportional and derivative). For each weight, an amplifier with a gain of about 45.5 is used. The proportional weight is adjusted from the RV1 potentiometer. The potentiometer RV2 is adjusting the derivative weight.
weight. Further, the two obtained signals are summed with the inverting summing amplifier U1: D. Finally, the output signal is optionally filtered and applied to the non-inverting input of the power amplifier U2. To analyse the efficiency of the circuit, the arbitrary voltage source, AVS1 was used in order to simulate the induced actuator’s coil voltage due to the vibration at the frequency of 200Hz and 4000Hz. The arbitrary voltage source, AVS2 is monitoring the voltage drop across the R17 resistor, which simulates the coil resistance of the actuator. The arbitrary voltage source AVS3 is monitoring the voltage drop across the inductor L1 that simulates the actuator's inductance. The voltages from the arbitrary voltage sources AVS 1 and AVS 2 are evidentiated on Figures 8 and 9.

The peak amplitude of the voltage on the equivalent series resistance was reduced from almost 250mV in figure 8 to below 50mV in Figure 9.

![Figure 8. Voltage drop on the actuator coil with both weights at zero and f = 200Hz. Red - induced voltage; blue - voltage on the equivalent series resistor (ESR); green - voltage on the equivalent series inductor (ESL).](image)

![Figure 9. Voltage drop on the actuator coil with proportional weight (P) at 54% and f = 200Hz. Red - induced voltage; blue - ESR voltage drop; green - ESL voltage drop.](image)
It should not be exaggerated with large weights because the system becomes unstable. Figure 10 shows that the system is unstable for a certain time after start-up.

Figure 10. Voltage drop on the actuator coil with weights P: 54%; D: 10% and f = 200Hz. Red - induced voltage; blue - ESR voltage drop; green - ESL voltage drop.

Figure 11. Voltage drop on the actuator coil with both weights at zero and f = 4000Hz. Red - induced voltage; blue - ESR voltage drop; green - ESL voltage drop.

Figure 12. Voltage drop on the actuator coil with proportional weights P: 26% ; D: 31% and f=4000Hz. Red - induced voltage; blue - ESR voltage drop; green - ESL voltage drop.
4. Experimental results
In order to test the system, a simple but effective test jig was created. For the electrodynamic exciter, a 4Ω, 25W small woofer was used. The electrodynamic actuator was a 16Ω smaller loudspeaker. Two piezoelectric tweeters were used as accelerometers. One of them was placed between the exciter and the actuator. The second one was placed on the smaller loudspeaker's membrane (element of interest for vibration reduction). A custom made signal generator was used to generate the sinusoidal signal that was applied to a custom made power amplifier. The amplified signal was applied to the exciter. For the feed-forward and negative impedance circuits, a breadboard was used for testing.

![Experimental workbench](image1)

Figure 13. Experimental workbench featuring the oscilloscope (1), a differential power supply distribution board (2), the custom signal generator (3), prototyping board (4), custom dual power amplifier (5) and the mechanical part (6).

![Mechanical part detail](image2)

Figure 14. Mechanical part detail, featuring the main woofer used as an electrodynamic exciter (a), support part (b), the first piezoelectric tweeter used as an accelerometer (c), the smaller woofer used as an actuator (d), the secondary tweeter (e) and the end part or isolated mass “m” (f).

Before and after photographs using the feed-forward system (40Hz).
Figure 15. Initial signals from both accelerometers with the disabled feed-forward circuit (the out-of-phase signal is sourced from the accelerometer mounted on the end part). Time base: 5 ms/div; Sensitivity: 10 mv/div; Both oscilloscope probes on 1X.

Figure 16. Final signals from both accelerometers with the enabled feed-forward circuit (the amplitude reduced signal is sourced from the accelerometer mounted on the end part). Time base: 5 ms/div; Sensitivity: 10 mv/div; Both oscilloscope probes on 1X. The noise on the second signal is due to noise pick-up from the custom made switching power supply used in the experiment and the extra pole created by the low-pass filter, using R21 and C4 (figure 7).

Photographs of the accelerometers signals using the negative impedance system (61 Hz).

Figure 17. Initial signals from both accelerometers with the disabled negative impedance circuit (the out-of-phase signal is sourced from the accelerometer mounted on the end part). Time base: 5 ms/div; Sensitivity: 10 mv/div; Both oscilloscope probes on 1X.
Figure 18. Signals from both accelerometers with the enabled negative impedance circuit with both weights at zero (the amplitude reduced signal is sourced from the accelerometer mounted on the end part). Time base: 5 ms/div; Sensitivity: 10 mv/div; Both oscilloscope probes on 1X.

Even with the weights set to zero, the vibration amplitude was reduced because the power amplifier was able to keep it's output very close to the ground potential. That means a low impedance condition. In this condition, the actuator is converting the mechanical energy into electric energy, dissipating it as heat. The power amplifier can manage this because most of the energy is dissipated into the coil.

Figure 19. Signals from both accelerometers with the enabled negative impedance circuit with P weight at 22% and the D weight at 63% (the amplitude reduced signal is sourced from the accelerometer mounted on the end part). Time base: 5 ms/div; Sensitivity: 10 mv/div; Both oscilloscope probes on 1X.

5. Conclusion
The designed, simulated and experimented system for semi-active vibration control did the job done, using the two related principles. The feed-forward principle was efficient for low frequency vibrations and the negative impedance principle managed to cope with medium and high frequency vibrations. For the negative impedance circuit, class D, I, T or other switching power amplifiers are not recommended because the high frequency noise will make the feed-back loop unstable. Even with class AB amplifiers, for the practical implementation of the schematic on Figure 7, the RC filter created with R21 and C4 can cause oscillations because of the extra pole that is created. If proper grounding and supply decoupling are ensured, this filter can be eliminated. In order to optimise the control law for each principle, software self-tuning can be added. For interaction with the related circuits (Figure 3 and figure 7), digital potentiometers can be used. The software must apply a tuning algorithm based on the description of each simulated circuit. Finally, the designed system can be easily implemented and optimised. The electronic schematics can be simulated and further optimised.
Because of the analog nature of the schematics, a high degree of reliability is ensured. The system was mostly designed for didactic purpose, it is also cheap and student friendly.

6. References

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