Enhanced Passive Vibration Suppression using Self-powered Piezoelectric Circuity Integration

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ABSTRACT

Negative capacitance can enhance the performance of piezoelectric based passive vibration suppression system using inductive shunting. However, the operational amplifier (op-amp) as the key component in the negative capacitance circuit consumes power, leading to additional power requirements to operate the system. In this research, we explore the feasibility of a self-powered circuitry that integrates together inductive shunting for vibration suppression, piezoelectric energy harvesting, and negative capacitance. Through systematic parametric analysis, we can identify a circuitry design that can take advantage of negative capacitance to enhance vibration suppression performance whereas the net power of the system remains to be positive. The results are validated experimentally.

Keywords: piezoelectric transducer, passive vibration suppression, energy harvesting, negative capacitance

1. INTRODUCTION

Piezoelectric based passive vibration suppression has been studied extensively [1]. The *RL* circuit, shunting the piezoelectric transducer, which electrically behaves as a capacitor, with an inductor and resistor, has shown to be effective [2]. Later studies attempted to further improve the performance, by means of impedance matching [3], tunable resonance [4], and multi-mode vibration control [5], etc. Meanwhile, the negative capacitance circuit is found to be beneficial in piezoelectric shunting [6]. With the usage of negative capacitance, the electro-mechanical coupling of the piezoelectric transducer can be increased, i.e., the capability of energy conversion is improved [7]. The negative capacitance integration can lead to further vibration suppression in *RL* shunt [8] and reduce the electrical component requirements [9]. However, the negative capacitance is realized by a synthetic circuit based on a negative impedance converter using operational amplifiers (op-amp) [10] that requires external power supply for operation. This generally turns the originally passive vibration suppression system into a semi-active vibration suppression system which requires external power supply.

This paper investigates the possibility of developing a self-powered circuitry integrating that combines together *RLC* resonant shunt and negative capacitance for enhanced vibration suppression, in which the energy harvesting potential of the piezoelectric transducer is exploited. In other words, we aim at using the piezoelectric transducer in the shunt circuit to harvest ambient energy and supply power to a rechargeable battery that drives the negative capacitance. The power consumption of op-amp is analyzed for the system. The power generation capability of the piezoelectric transducer in the shunt circuit is also investigated. Based on the net power analysis, the selection criteria of the negative capacitance value to guarantee positive net power is provided. The rest of the paper is organized as follows. The analysis of the piezoelectric vibration suppression system with and without negative capacitance is presented in Section 2. The self-powering strategy is illustrated in Section 3, followed by experimental validation provided in Section 4. The conclusions are summarized in Section5.

2. ANALYSIS OF VIBRATION SUPPRESSION SYSTEM

As shown in Figure 1, A general piezoelectric vibration suppression system consists of a cantilever beam as the host structure with a piezoelectric transducer bonded onto it and a piezoelectric shunt connected. Here, both the *RL* circuit and negative capacitance are integrated into the piezoelectric shunt.

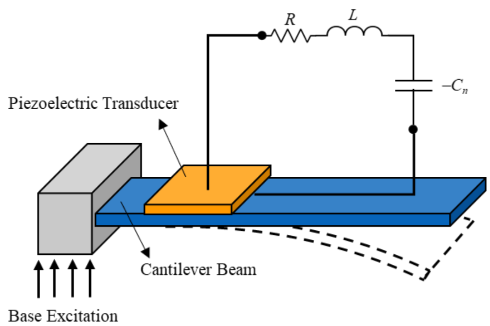

Figure 1. Resonant piezoelectric vibration suppression system with negative capacitance integration

Based on the Euler-Bernoulli beam theory, the simplified model can be obtained [11] and the system equations can be derived as

$$\begin{cases} m\ddot{q} + g\dot{q} + kq + k_1 Q = F_m \\ L\ddot{Q} + R\dot{Q} + k_2 Q + k_1 q = 0 \end{cases} \tag{1}$$

where q is the vibration displacement, and Q is the charge flow. m, g, k are equivalent mass, beam equivalent damping, and equivalent stiffness coefficients related to the mechanical structure. k_1 is equivalent electro-mechanical coupling coefficient of the piezoelectric patch. L, R, k_2 are inductance, resistance, and inverse of inherent capacitance of piezoelectric patch C_p. F_m is the harmonic excitation. The transfer function between the mechanical displacement and external force, and that between the electrical charge and external force are derived as

$$\frac{\bar{q}}{\bar{F}_m} = \frac{\left(\omega^2 L - i\omega R - k_2\right)}{\left(-m\omega^2 + i\omega g + k\right)\left(\omega^2 L - i\omega R - k_2\right) + k_1{}^2} \tag{2}$$

$$\frac{\bar{Q}}{\bar{F}_m} = \frac{k_1}{\left(-m\omega^2 + i\omega g + k\right)\left(\omega^2 L - i\omega R - k_2\right) + k_1{}^2} \tag{3}$$

For optimal vibration suppression, the inductance and resistance [11] are selected as

$$L_{\text{opt}} = \frac{k_2 m}{k}, \qquad R_{\text{opt}} = \frac{k_1}{k}\sqrt{2mk_2} \tag{4a,b}$$

Without negative capacitance integration, the parameter k_2 is the reciprocal of the inherent capacitance C_p. Whereas, with negative capacitance integration, the parameter k_2 changes to $\hat{k}_2$ as

$$\hat{k}_2 = k_2 - \frac{1}{C_n} = \frac{1}{C_p} - \frac{1}{C_n} \tag{5}$$

where C_n is the negative capacitance value.

It is shown in Equation (5) that with the negative capacitance integration, the parameter k_2 can be reduced. This results in the increase of the generalized electro-mechanical coupling coefficient of the piezoelectric transducer $\xi = k_1 / k\hat{k}_2$. Combing negative capacitance with *RL* shunt, the vibration suppression performance can be enhanced. In Figure 2. When the negative capacitance value is small enough (20nF) to be close to the inherent capacitance value (11.41nF), significant vibration suppression enhancement can be observed. When the negative capacitance value becomes larger, the enhancement of vibration suppression decreases.

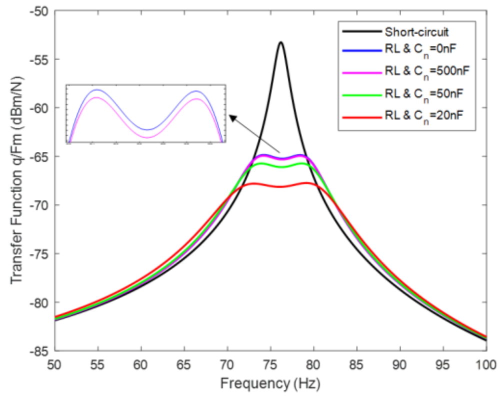

Figure 2. Vibration suppression with negative capacitance integration

3. SELF-POWERING STRATEGY

In conventional passive vibration suppression system, the piezoelectric shunt is utilized to dissipate the generated energy. In this research, we propose to integrate energy harvesting into the system. In this case, the resistance element in the *RL* shunt will be replaced by an interface circuit in energy harvesting system. The capability of energy harvester is commonly analyzed by the power of the resistor load. Therefore, the power available for energy harvesting is represented as

$$\bar{P}_s = \bar{I}^2 \cdot R = \left(i\omega\bar{Q}\right)^2 \cdot R \tag{6}$$

Our goal is to investigate whether such power is sufficient to overcome the power consumption of the negative capacitance. If the answer is yes, in practical implementation we can supply the power to a rechargeable battery and use the rechargeable battery to drive the negative capacitance. If the net power is greater than zero, we can realize self-powering for vibration suppression performance enhancement with negative capacitance.

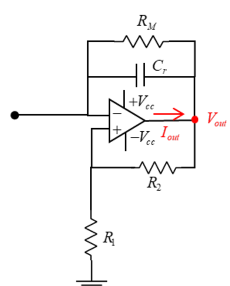

Figure 3. Negative capacitance circuit diagram

The circuit diagram of a representative negative capacitance circuit is shown in Figure 3, and the negative capacitance value C_n can be expressed as [9]

$$-C_n = -\frac{R_2}{R_1}C_r \tag{7}$$

where C_r is the reference capacitance, R_1 and R_2 are the resistances to determine the magnification of the reference capacitance.

The power consumption of op-amp in negative capacitance circuit can be derived as

$$\bar{\hat{P}}_{\text{op-amp}} = \bar{I}_{\text{out}} \cdot \bar{V}_{\text{out}} = \left(\frac{\left(R_1 + R_2\right)\left(1 + i\omega C_r R_2\right)}{R_1^2}\right) \cdot \bar{V}_{\text{in}}^2 \tag{8}$$

where $\bar{V}_{\text{out}}$ and $\bar{I}_{\text{out}}$ are the output voltage and current of the op-amp. The power consumption effect of op-amp is owing to the outward direction of the current at the output terminal of op-amp. $\bar{V}_{\text{in}}$ is the input voltage of the negative capacitance circuit, which can be derived based upon the negative capacitance circuit as

$$\bar{V}_{\text{in}} = \frac{\bar{Q}}{-C_n} \tag{9}$$

where the input charge of the negative capacitance circuit is actually equal to the charge in the piezoelectric shunt $\bar{Q}$.

The net power is defined as the amplitude difference between the available power in resistance and the power consumption of op-amp. Based on Equation (6) and Equation (8), the amplitudes of the available power in resistance and power consumption of op-amp can be obtained, then the final net power amplitude is derived as

$$\begin{aligned} \left|\frac{\bar{P}_{\text{net}}}{\bar{F}_m^2}\right| = \left|\frac{\bar{P}_s}{\bar{F}_m{}^2}\right| - \left|\frac{\bar{P}_{\text{op-amp}}}{\bar{F}_m^2}\right| &= \frac{k_1^2\left[\omega^2\hat{R} - \frac{(R_1+R_2)}{R_1^2C_n^2}\cdot\sqrt{1+\omega^2R_1^2C_n^2}\right]}{\left|A^2+B^2\right|} \\ A = \left(k-m\omega^2\right)\left(\omega^2\hat{L}-\hat{k}_2\right)+k_1{}^2+\omega^2 g\hat{R} \\ B = \omega g\left(\omega^2\hat{L}-\hat{k}_2\right)+\hat{R}\omega\left(m\omega^2-k\right) \end{aligned} \tag{10}$$

where the inductance and resistance are the optimal values under the integration of negative capacitance, which can be obtained by combining Equation (4) and Equation (5).

In order to realize self-powering negative capacitance, the net power must be greater than zero. From Equation (10), we can derive

$$\left[\omega^2\hat{R} - \frac{(R_1+R_2)}{R_1^2C_n^2}\cdot\sqrt{1+\omega^2R_1^2C_n^2}\right] > 0 \tag{11}$$

Here, we set $R_1 = R_2$ to simplify the design. In this case, based on Equation (7) we have $C_n = C_r$. The critical value of the negative capacitance than can yield positive net power can be derived as

$$C_n^4 - \frac{1}{k_2}C_n^3 - \frac{2k}{k_2k_1^2}C_n^2 - \frac{2m}{k_2R_1^2k_1^2} = 0 \tag{12}$$

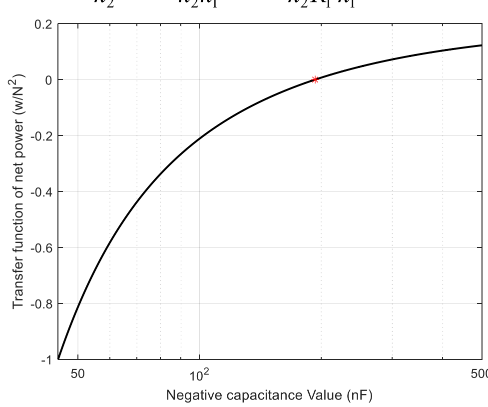

Figure 4. Transfer function between the net power and the excitation

As shown in Figure 4, there indeed exists a critical negative capacitance value above which the net power is greater than zero. Also, with larger negative capacitance value, the net power increases. Nevertheless, it is worth noting than larger negative capacitance value generally reduces the benefit of negative capacitance to vibration suppression enhancement. Therefore there is a trade-off.

4. EXPERIMENTAL RESULTS

A shaker (APS 400) connected with a power amplifier (APS 145) is utilized to apply the external excitation to the structure. A controller (VR9500) is used to control the excitation with a constant acceleration by the feedback measurements of the accelerometer (PCB 352C04). The voltage measurements are realized by the oscilloscope (Keysight DSOX1204G) to obtain the experimental power results. The mechanical vibration is measured by a vibrometer (Polytec PSV-500).

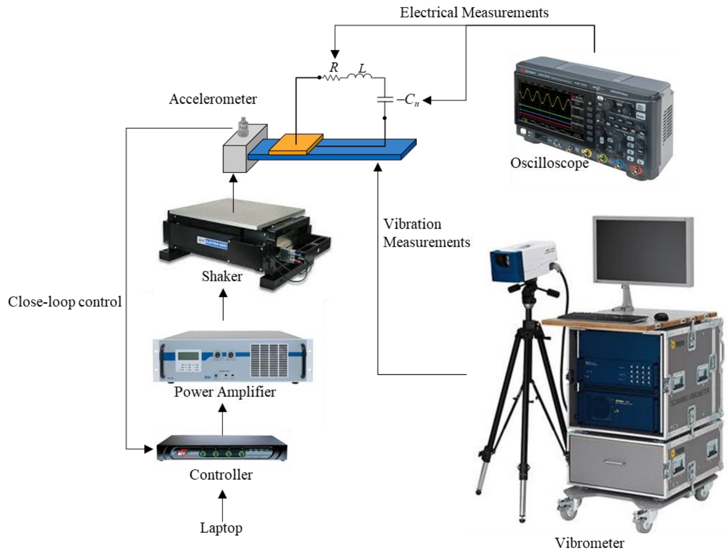

Figure 5. Experimental setup

The inherent capacitance of the piezoelectric patch is measured as 11.24nF. The experimental open-circuit and short-circuit natural frequencies are 76.5234Hz and 76.1797Hz, respectively. According to Equation (12), the critical negative capacitance of the experimental structure is 173.62nF, which means that when the negative capacitance value is selected to be larger than 173.62nF, the net power can be maintained positive, and the system can achieve self-powering. In order to validate this, two different negative capacitance values which are larger than critical negative capacitance value (173.62nF) are chosen as 882nF and 313nF. As mentioned in Equations (4) and (5), resistance and inductance are selected as optimal values under each negative capacitance value. The experimental results of the net power frequency response are reported in Figure 6. Similar to the plateau-like pattern neat the natural frequency of the analytical vibration frequency response shown in Figure 2, the frequency response of the electrical net power has plateau like pattern. For both negative capacitance values (882nF and 313nF) selected within the proposed selection criteria (Equations (11) and (12)), the results of the net power amplitudes are positive. It is also worth noting that the larger negative capacitance value (882nF) shows higher net power, which matches well to the analytical results in Figure 4. This confirms the validity of the critical negative capacitance and positive net power analysis.

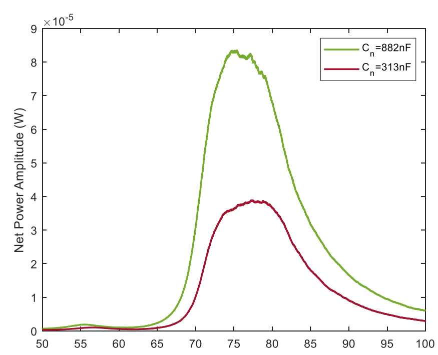

Figure 6. negative capacitance integration

We then analyze the vibration suppression performance under those two negative capacitance values (882nF and 313nF). The experimental results of the frequency responses of the vibration are reported in Figure 7. As can be observed, with a negative capacitance integration, the vibration suppression performance is further enhanced. Compared to the *RL* circuit without negative capacitance, the shunt with larger negative capacitance value (882nF) further suppresses the vibration velocity by around 5.91%, while the RL shunt with smaller negative capacitance value (313nF) further suppresses the vibration velocity by around 11.79%. This demonstrates the validity of the enhanced vibration suppression owing to negative capacitance integration. For this experimental structure, the critical negative capacitance value is 173.62nF. When the negative capacitance value is selected to be closer to the critical negative capacitance value, larger vibration suppression enhancement can be seen, while smaller net power can be harvested.

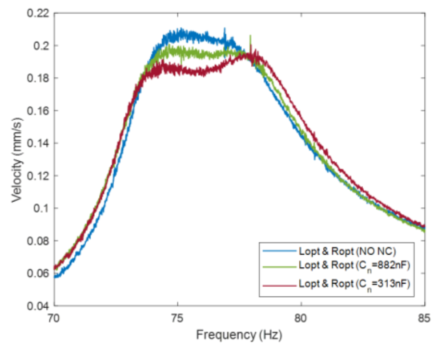

Figure 7. Further enhanced vibration suppression due to negative capacitance integration

5. CONCLUSION

In this research, we study the development of a self-powering circuitry to integrate negative capacitance and *RL* shunt for both enhanced vibration suppression and energy harvesting. Based on the analyses of the power consumption of op-amp and available power for harvesting, the net power investigation is conducted. Our results indicate that it is indeed possible to identify a range of negative capacitance values within which the net power is greater than zero. Our experimental investigations confirm that vibration suppression enhancement can be realized with the integration of negative capacitance, and that the net power within the desired range is indeed positive.

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