EXPERIMENTAL VALIDATION OF PIEZOELECTRIC SHUNT DAMPING BY USING CURRENT CONVEYOR BASED INDUCTORS

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It is well-known that the structural vibration can be reduced by using piezoelectric shunt resonant damping techniques. To achieve optimal control performance, the natural frequency of the shunt circuit should be close to the targeted natural frequency of the vibrating structure. In the low frequency range, a high value inductance (several or dozens of henrys) are required. The inductance simulators are typically used by using operational amplifiers, such as the Antoniou circuit. In this paper, the active inductance simulator based on second generation current conveyor (CCII) is used to design the piezoelectric shunt circuit. The effectiveness of the traditional inductance simulators and CCII based simulators is discussed and compared. Finally, with an example of clamped-clamped beam, the vibration control performances based on RL series circuit with different inductance simulators are experimentally analyzed and compared. Experimental results show that the vibration of the beam can be reduced significantly by using these shunt circuits with optimal parameters. Furthermore, it is found that the piezoelectric shunt circuit based on CCII inductance simulator has better control performance than traditional one.

Keywords: Piezoelectric shunt damping, current conveyor, inductance simulators, passive control

1. Introduction

The vibration control of a flexible structure by using piezoelectric materials has become an important topic in the past two decades. Piezoelectric transducers (PZTs), in conjunction with appropriate proper electrical circuit, can be used as a mechanical energy dissipation device. This practice is known as piezoelectric shunt damping. Recently, many types of shunt circuits [1 – 10], such as RL series, RL parallel, RL-C parallel and the synchronized switch circuits, have been proposed, these typical shunt circuits are shown in Fig. 1.

Figure 1: Several typical piezoelectric shunt circuit. (a) RL series; (b) RL parallel; (c) RL-C parallel; (d) synchronized switch.
If the network consists of a series inductor–resistor (RL series) circuit, the passive network combined with the inherent capacitance of the PZT creates a damped electrical resonance. The natural frequency of the circuit should be close to the natural frequency of the targeted mode. Since the values of inductors can be high to several or dozens of henrys at low frequencies, there is a necessity for the replacement of the inductor by using inductance-simulator circuit. One of most popular such circuit is Antoniou inductor simulator circuit based on classical voltage operational amplifiers. In more recent years, the second-generation current conveyors (CCII) [11] were developed as an alternative to the classical voltage operational amplifiers (OPA). Unlike OPAs, CCIIIs are current-based and they operate according to the principle of “current conveying” from one terminal to another. In this study, shunt circuit designed by using CCII technology is presented. Finally, with the example of a clamped-clamped beam, the proposed CCII based shunt circuit is experimental verified.

2. CCII-based grounded inductance-simulator

2.1 Basic CCII theory

The main principle of CCIIIs is conveying current from one terminal to another terminal [12 – 16]. CCII is a three-port device, and the block diagram is shown in Fig.2. Under ideal conditions, its terminal voltage and current input and output characteristics can be represented as [14]

\[
\begin{bmatrix}
    i_x \\
    V_x \\
    i_z
\end{bmatrix} =
\begin{bmatrix}
    0 & 0 & 0 \\
    1 & 0 & 0 \\
    0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
    V_y \\
    i_e
\end{bmatrix}.
\]  

(1)

![Figure 2: (a) Symbol of CCII; (b) CCII block diagram with parasitic elements](image)

From Eq. (1) and Fig. 2, it can be found that the principle of operation of CCII is as follows: (a) If a \( V_y \) voltage is applied to the Y terminal, the same voltage will appear at terminal X, such as \( V_x = V_y \); (b) There is no current flowing into the Y terminal, \( i_y = 0 \); (c) If there is a current flowing into X terminal, the same current will also flow into the Z terminal, such as \( i_x = i_z \).

2.2 Inductance-simulator design

Using CCIIIs and certain combination of passive elements like resistors and capacitors, it is possible to simulate both floating and grounded inductors. Ref.[11] proposed a inductance-simulator circuit by using three CCIIIs type current conveyors, as shown in Fig. 3. This circuit has an impedance \( Z_i = V_y/i_i \) given by

\[
Z_i = j\omega L_{eq} \quad \text{and} \quad L_{eq} = R_1 R_2 C_1.
\]  

(2)

where \( j = \sqrt{-1} \), \( \omega \) is frequency, \( R_1 \) and \( R_2 \) are resistances and \( C_1 \) is capacitance.

From Eq. (2), it can be found that the circuit shown in Fig. 3 is an equivalent grounded inductance. However, this circuit is only available for ideal case, because the parasitic resistances and capacitances in CCII were not considered.
To overcome this problem, a modified inductance-simulator circuit is proposed, as shown in Fig. 4.

For this circuit, we can write

\[ I_i \equiv I_{z1} = I_{x1} = I_{z3} = I_{x3} = \frac{V_{x3}}{R_2}. \]  
\[ (4) \]

\[ V_{x3} = V_{y3} = V_{z2} = \frac{I_{z2}}{j\omega C_1}. \]  
\[ (5) \]

Substituting Eq. (5) into Eq. (4), we get

\[ I_i = \frac{I_{z2}}{j\omega R_2 C_1}. \]  
\[ (6) \]

Since

\[ I_{z2} = I_{x2} = \frac{V_{x2}}{R_1}. \]  
\[ (7) \]

We get

\[ I_i = \frac{V_{x2}}{j\omega R_1 R_2 C_1}. \]  
\[ (8) \]

Notice that \( V_{x2} \) can be expressed as
\[ V_{X_2} - V_I = I_j R_j \quad \text{and} \quad V_{X_2} = I_j R_j + V_I. \]  

Substituting Eq. (9) into Eq.(8), the impedance of this circuit can be obtained

\[ I_{X_2} = I_{Z_2}. \]  

\[ Z_I = \frac{V_I}{I_I} = j \omega R_i R_s C_1 - R_j. \]  

Clearly, from Eq.(10), the equivalent inductance and resistance for circuit shown in Fig. 4 are

\[ L_{eq} = R_s R_j C_1 \quad \text{and} \quad R_{eq} = -R_j. \]  

The negative resistance in Eq.(11) is used to cancel the parasitic resistance in CCII. It can also be found that the values of the equivalent inductance and equivalent resistance can be tuned independently.

### 3. Experimental investigations

In order to demonstrate the control performance of the piezoelectric shunt damping with the proposed inductance-simulator, an experimental test was performed on a vibrating beam. This experiment is intended to demonstrate the proposed inductance-simulator and to compare with traditional Antoniou inductor simulator in a real vibrating system. And the integrated circuit AD844 fabricated by Analog Devices was used as CCII. A 345mm×30mm×5mm aluminium beam with two PZT elements (One is used as primary source and another is used for the shunt circuit), and one accelerometer bonded near the center of beam was used to monitor the control performance for each tests. The beam was clamped at both ends.

All frequency response functions (FRFs) were measured, from the voltage output of the accelerometer to the voltage input the primary PZT actuator. A TST5912 dynamic signal analysis system was used to create the excitation signal and perform all FRFs measurements. The goal of the experiment was to control the third structural mode (with natural frequency 234.2Hz) of the beam.

![Figure 5: experimental set-up](image)
The capacitor of PZT used in the experiment is $C_p = 130\text{nF}$. The natural frequency of the shunt circuit was tuned to the targeted frequency (234.2Hz), the value of inductance should be 3.55H. So we set the components used in shunt circuit (see Fig. 4) as $C_1 = 100 \text{nF}$, $R_1 = 10 \text{k\Omega}$, $R_2 = 3.55 \text{k\Omega}$. And $R_3$ is set to 190\text{\Omega} after a trial and error search in this study. For comparison, the shunt circuit based on the traditional Antoniou inductor simulator (as shown in Fig. 6) was also performed, it is well-known that the equivalent inductance for circuit in Fig.6 is $L_{eq} = C_4 R_1 R_3 R_5 / R_2$. The value of the equivalent inductance was also tuned as 3.55H for comparison.

![Figure 6: Principle diagram of Antoniou inductance-simulator circuit](image)

First, the beam was excited by sinusoidal signal with frequency at 234.2Hz (the third natural frequency of the beam). Figure 7 shows the control performances for shunt circuit by using these two inductance-simulators. From Fig.7, it can be found that the vibration of the beam can be reduced significantly by using both shunt circuits. However, it is found that the shunt circuit based on CCII inductance-simulator has better control performance than traditional Antoniou inductance-simulator.

![Figure 7: Time-domain responses. (a) CCII inductance-simulator; (b) Antoniou inductance-simulator](image)
To further compare the control performance, the beam was excited by sweep signal. Figure 8 shows the frequency response function for these two shunt circuits under different resistance value and optimal inductance value. It can be found that control performance of both RL series circuits deeply depends on the resistance values. If the value of resistance is too large, the shunt circuit becomes uncoupled with the structural mode and there is little improvement in the damping performance. Alternatively, if only small resistances are added, two new lightly damped structural modes occur. Figure 9 compares the control performances for CCII-based and Antoniou-based shunt circuits under optimal resistance values. It is clearly that the CCII-based shunt circuit can obtain the better control performance.

Figure 8: The frequency response function for (a) CCII inductance-simulator; (b) Antoniou inductance-simulator
4. Conclusions

In this study, the piezoelectric shunt damping based on CCII technology is presented. It provides an alternative way to design the inductance-simulator for shunt circuits. The proposed CCII circuit can tune its equivalent inductance and equivalent resistance independently. And the proposed CCII-based shunt circuit is experimentally compared to traditional Antoniou-based shunt circuit. The experimental results show that, both shunt circuits can reduce the vibration of the beam significantly. Furthermore, it is found that the proposed CCII-based shunt circuit can obtain the better control performance.

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