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Publication date:
2019

Document Version
Peer reviewed version

Citation (APA):
Toftekær, J. F., & Høgsberg, J. (2019). *Multi-Mode Piezoelectric Shunt Damping of Plate-Like Structures*. Abstract from 30th International Conference on Adaptive Structures and Technologies, Montreal, Canada.

ICAST2019: 30th International Conference on Adaptive Structures and Technologies
October 7-11, 2019, Montreal, QC, Canada

Multi-Mode Piezoelectric Shunt Damping of Plate-Like Structures

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Abstract
Excessive resonant vibration of flexible plate-like structure may be mitigated by the attachment of shunted piezoelectric absorbers. The resonant shunt circuit consists of an inductor and a resistor tuned with respect to a target resonant frequency of the structure. When several shunted piezoelectric absorbers are attached to the vibrating structure more resonant vibrations may be mitigated simultaneously. A calibration procedure for the tuning of several shunted piezoelectric absorbers is demonstrated experimentally for a free beam and a plate structure with five piezoelectric transducers simultaneously mitigating four resonant vibration modes. Experimental results correlate well with numerical results.

Introduction
Flexible plate-like structures may be vulnerable to excessive vibrations caused by dynamic harmonic loads with frequencies close to a resonance in the structure. This may cause structural failure, fatigue or lead to undesirable acoustic problems. The introduction of resonant absorber devices calibrated to a single or several dominating resonant modes of the structure may therefore be required. Regarding vibration mitigation of plate-like structures, a convenient absorber device consists of co-located piezoceramic patches with strong electromechanical coupling properties wired to a resonant shunt circuit, (Toftekær et al., 2019). The resonant shunt circuit consists of an inductance (L) tuned to secure a proper absorber frequency and a resistor (R) chosen to obtain optimum energy dissipation around the targeted resonant frequency.

Method and Model Formulation
The calibration of LR shunts is typically based on the assumption of a modal reduced system, representing the full structural dynamic response around the targeted resonant frequency. This assumption leads to inaccuracies in the corresponding shunt tuning when spill-over from non-resonant vibration modes is neglected. A recent piezoelectric shunt tuning procedure (Toftekær and Høgsberg, 2019) is based on the absorber response given as, respectively, the measured electric current and voltage associated with the short- (SC) and open circuit (OC) piezoelectric interface electrodes, inherently containing the contribution from non-resonant vibration modes, see Tab. 1. This method is a refinement of the method proposed in Toftekær et al., (2019) and is verified experimentally. Regarding the numerical implementation, two eigenvalue problems associated with SC and OC piezoelectric interface electrodes are evaluated, while the experimental implementation requires two frequency response functions (FRF) to be determined from the electric current and voltage response to random dynamic loading of the tested structure. The numerical method is presented for single- and multi-mode tuning in Toftekær and Høgsberg (2019).
The current experimental setups, concerning a free aluminum beam Fig. 1(b) and plate Fig. 1(c) with five pairs of collocated piezoceramic patches verifies the optimum multi-mode shunt tuning procedure in

Table 1. Resonant parallel shunt tuning of n_p circuits with respect to target mode r of piezoelectric transducer i and the corresponding squared electromechanical coupling coefficient κ_r^2, damping ratio ζ_r and modal mass $\tilde{m}_r$

$L_i^p = \dfrac{\lvert\hat{V}_r\rvert_i}{\lvert Q_r\rvert_i \omega_r^2}$	$R_i^p = \dfrac{\lvert\hat{V}_r\rvert_i}{\lvert Q_r\rvert_i \omega_r}\sqrt{\dfrac{1}{2\kappa_r^2}}$	$\kappa_r^2 = \sum_{i=1}^{n_p} \dfrac{\lvert Q_r\rvert_i \lvert\hat{V}_r\rvert_i}{\tilde{m}_r \omega_r^2}$	$\zeta_r = \sqrt{\dfrac{1}{8}\kappa_r^2}$

Toftekær and Høgsberg (2019). In the experimental setup in Fig. 1(a), the power amplifier excites the structure by a single pair of piezoceramic patches, while the Laser Doppler vibrometer measures the mechanical velocities, from which dynamic amplifications, frequencies and mode-shapes may be determined. Finally, the multimeter measures the electric current and voltage response of the four remaining pairs of piezoceramic patches. The optimum piezoelectric shunt tuning in Tab. 1 is then determined from the SC and OC frequencies (ω_r and $\hat{\omega}_r$) and modal charge $|Q_r|_i$ and voltage $|\hat{V}_r|_i$ estimated from the FRFs for the electric current and voltage, respectively. The shunt circuits are then implemented by an inductance realized by winding a copper wire around a magnetic coil connected to a variable resistor.

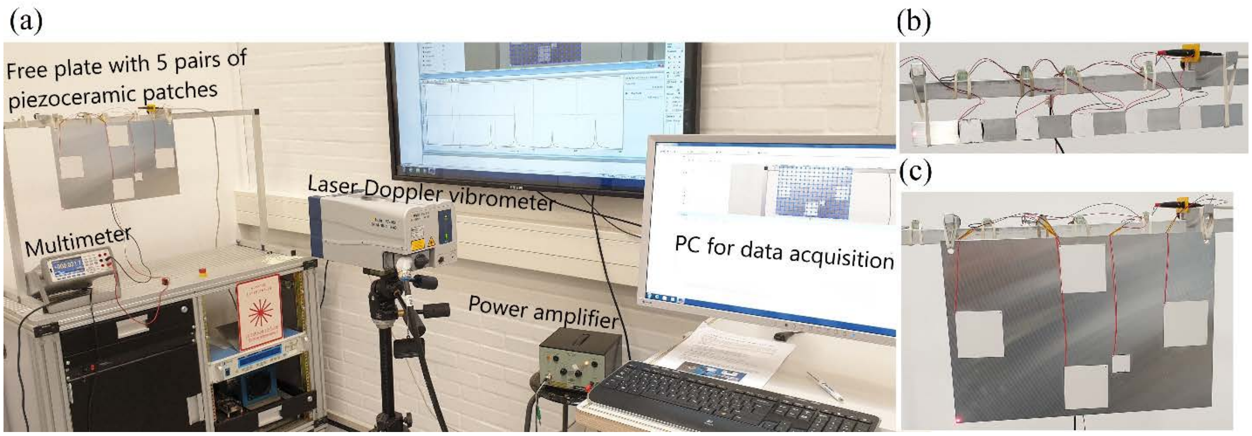

Figure 1. Experimental setup (a) and close-up of the tested free (b) beam and (c) plate with five pairs of co-located piezoceramic patches.

Results and Discussions

The FRFs for charge and voltage of four of the piezoceramic patch pairs attached to the free beam and plate are attained from the time records to random vibration excitations induced by the patch pair connected to the power amplifier. From the FRFs, see Fig.2, the tuning parameters required in Tab. 1 are obtained and the corresponding shunt tuning is determined for all resonant modes in the considered frequency spectrum.

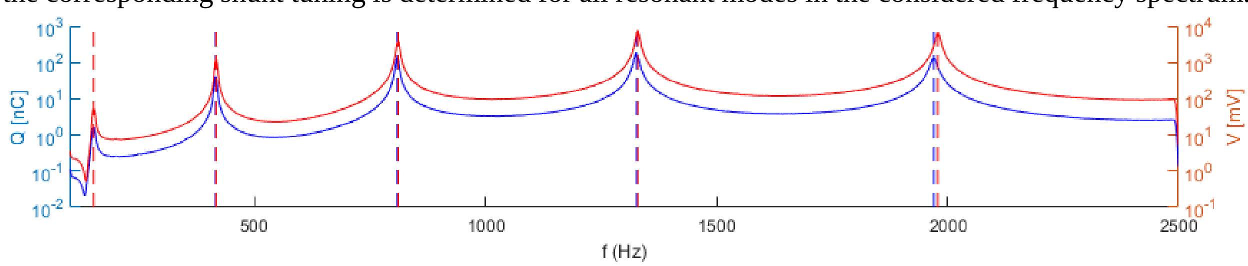

Figure 2. FRF for electric current and voltage for the left piezoceramic patch pair on the free beam Fig. 1(b).

The calibration procedure (Toftekær and Høgsberg, 2019) is found to perform well for both single and multi-mode vibration mitigation and the results are in good correlation with the results obtained with corresponding numerical models build in ANSYS® with 3D finite elements (Toftekær and Høgsberg, 2019). While the tuning of the shunt inductance correlates well, the resistance tuning is more uncertain due to lower electromechanical coupling coefficients and parasitic damping in the experiment from mainly a non-ideal gluing of the piezoceramic patches.

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