Comparison of Wave Sensing Stragegies for Active Structural Acoustic Control

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1 Introduction

Among the strategies available for the active control of energy transmission from one area of a structure to another area, the control of travelling waves, structural intensity or power flow can all be considered. The previous intensity or power flow control strategies usually assumed far field propagation and are based on an estimate of the exact structural energy flow [1, 2].

It is thererefore the purpose of this paper to present a strategy using strain sensing for the control of structural intensity associated with flexural motion in a coupled beam/plate mechanical system and compare it with a strategy based on the control of the acceleration at one point on the structure. The instantaneous intensity is completely taken into account in the control algorithm, *i.e.* all the terms are considered in the real-time control process and, in particular, the evanescent waves are considered in this approach. Previous work has shown the validity of this energy-based approach using acceleration sensing [3]. The approach is limited to cases where the geometry is such that the intensity at the error sensor will have the same sign for the control source and the primary disturbance.

2 Structural intensity measurement using strain sensing

2.1 Flexural structural intensity in a beam

The structural intensity is the instantaneous rate of vibrational energy transfer, or energy flow, per unit area in a given direction. The instantaneous energy flow in a beam, called the instantaneous structural intensity (subscript $_i$) in this paper, originating from a flexural displacement $w(x,t)$, can be expressed for an Euler-Bernoulli isotropic beam:

$$\vec{I}_i^{\,f} = \left(EI\frac{\partial^3 w}{\partial x^3}\right)\left(\frac{\partial w}{\partial t}\right)\vec{i} - \left(EI\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial^2 w}{\partial t \partial x}\right)\vec{i} \tag{1}$$

where E is the Young's modulus, I the area moment of inertia of the beam and $\vec{i}$ the unit vector in the x direction. The control algorithm will minimize the time average of the instantaneous intensity, called the active intensity.

2.2 Finite differences implementation

Since four discrete strain sensors are used to estimate the structural intensity, it is necessary to develop a finite differences approximation based on strain sensing to measure structural intensity associated with flexural motion in beams. The flexural strain ε_z is related to the flexural displacement by $\varepsilon_z(x,t) = \dfrac{\partial^2 w(x,t)}{\partial x^2}$. The instantaneous intensity is evaluated at the center of the probe, x_e, with an error on the order of Δ, Δ being the spacing between two consecutive sensors. The time differentials of strain in equation (1) are estimated using a backward finite difference scheme with error on the order of τ^2, where τ is the time increment between samples.

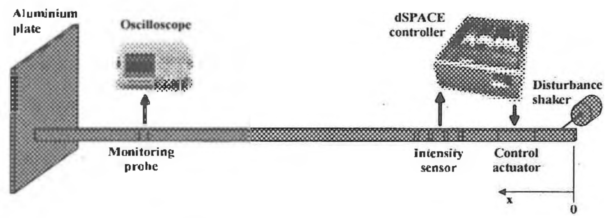

Figure 1: Experimental setup.

3 Experimental validation

3.1 Experimental setup

The Fig. 1 shows the experimental setup used for the control. The structure is a plate ($0.48m \times 0.42m \times 0.003m$) connected to a beam ($3m \times 0.0254m \times 0.003m$) made of aluminium covered on one side by a *ISD 830* viscoelastic material combined with a constraining aluminium foil. The viscoelastic material is used to increase the structural damping such that the intensity signal can be measured.

The disturbance is generated by a *Bruel & Kjaer 4810* shaker connected to the beam by a stinger at one end of the beam. The control actuator consists of a PZT patch actuator (*PSI-5A-S2*). The coordinates of the edges of the patch are $0.2m$ and $0.27m$ from the shaker taken as the origin of coordinates. The coordinates of the four PVDF strain sensors are $x_1 = 0.22m$, $x_2 = 0.26m$, $x_3 = 0.3m$ and $x_4 = 0.34m$. The accelerometer used for acceleration control is located in the middle of the PVDF sensors array at $x_e = 26.5cm$. Two accelerometers located at $2.09m$ and $2.19m$ are used for monitoring the control and the mean RMS value of these signals is used as a performance indicator.

The control of instantaneous intensity and of acceleration were experimentally performed using a feedforward filtered-X least mean square algorithm (FX-LMS) [2] adapted to this energy-based cost function. The output control signal $\mathbf{Y}(m)$ at the actuators is obtained by filtering the reference signal $\mathbf{X}(m)$ by the control filter $\mathbf{W}^T(m)$ which is updated using $\mathbf{W}(m+1) = \mathbf{W}(m) - \mu_0 \nabla_W I_i(m)$ where μ_o is a parameter taken to ensure convergence and $\nabla_{\mathbf{W}} I_i(m)$ is the gradient of the error surface with respect to the coefficients of the control filter given by $\nabla_{W_f} I_i = [\mathbf{R}_1 e_2 + \mathbf{R}_2 e_1 - \mathbf{R}_3 e_4 - \mathbf{R}_4 e_3]$ where the four error functions e_i corresponding to the four physical quantities involved in the instantaneous intensity (Eq. (1)) can be defined as:

$$e_1(m) = \frac{\partial \varepsilon_{zp}}{\partial x}(m) + \mathbf{W}^T(m)\mathbf{R}_1(m) \tag{2}$$

$$e_2(m) = \frac{1}{k^4}\frac{\partial^3 \varepsilon_{zp}}{\partial t \partial x^2}(m) + \mathbf{W}^T(m)\mathbf{R}_2(m) \tag{3}$$

$$e_3(m) = \varepsilon_{zp} + \mathbf{W}^T(m)\mathbf{R}_3(m) \tag{4}$$

$$e_4(m) = \frac{1}{k^4}\frac{\partial^3 \varepsilon_{zp}}{\partial t \partial x^3}(m) + \mathbf{W}^T(m)\mathbf{R}_4(m) \tag{5}$$

where $\mathbf{R}_i$ are the corresponding filtered reference signals and where the flexural wavenumber is $k = \left(\frac{\rho S}{EI}\omega^2\right)^{1/4}$, where ρ is the density, S is the section of the beam and ω is the angular frequency.

The algorithm was implemented on a *dSPACE* prototyping environment, equipped with three *DEC Alpha* processors. The reference input signal was taken as the signal from the generator that drives the disturbance shaker. The sampling rate was set at $3kHz$ in the experiments. A piezoelectric patch is used to inject the control signal in the structure, in the form of two moments along its two edges.

3.2 Experimental control results

The Fig. 2 presents some typical control results obtained using two different approaches. The mean RMS value measured at the two monitoring accelerometers is presented in this figure, using two different strategies. The first strategy aims at minimizing the acceleration level at the point x_e. The second strategy aims at minimizing the structural intensity with the sensor centered at x_e. These preliminary results indicate that the intensity suffers from convergence problems, indicated by points superimposed with the without control curve, while the acceleration control algorithm converges over the entire frequency band. Apart from these convergence problems, the control of intensity tends to perform adequately on the resonances below 350 Hz while intensity and acceleration control behave almost the same above this frequency. The location of the actuator explains the lost in the performance of both algorithms

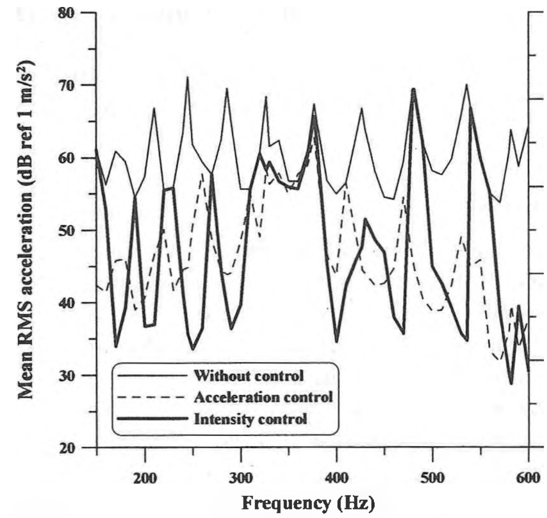

Figure 2: Two structural active control strategies.

around 350 Hz. Three reasons could explain the problems noticed with intensity algorithm: 1) the PVDF sensors signals were not filtered, which could lead to spurious energy in the frequency band of interest, 2) the extensional waves were not considered in the intensity algorithm, it is suspected that a coupling between the two types of waves leads to poor performance of the control algorithm and 3) low and high frequency limitations arise due to the limited accuracy of the measurement including the finite difference scheme.

4 Conclusions

The control of flexural intensity in complex structure originating from point force and using a piezoelectric patch actuator has been experimentally validated by comparison with a classical acceleration control. High attenuation of the mean RMS acceleration downstream of the error sensor location can be achieved when controlling harmonic disturbance with a piezoelectric patch. Some problems have been identified with the intensity control algorithm and reasons have been proposed to tentatively explain these problems. Work is in progress to alleviate these limitations.

References

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