An error intensity spectral filtering method for active control of broadband structural intensity

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(Received 14 August 1995; revised 22 April 1996; accepted 20 August 1996)

The implementation of structural intensity measurement using an accelerometer array allows active attenuation of broadband frequency vibration using a modified filtered-x algorithm. In this work, a multi-input channel accelerometer error filter outputs a single channel error signal proportional to the propagating power. The filter is specified in the frequency domain as a transfer function from a model of bending waves in a finite beam. Integrity of the beam model and active control simulations is verified by monitoring an acceleration in the far field. The best overall performance is achieved when the error sensor array is in the far field of the primary and adaptive control force actuators. Broadband application of the intensity error technique in physical model-based simulations showed 15- to 25-dB attenuation except at a few isolated frequencies. These preliminary simulation results support new approaches to active stuctural control through error sensor array processing. © *1997 Acoustical Society of America.* [S0001-4966(97)00101-X]

PACS numbers: 43.40.Vn [PJR]

INTRODUCTION

In this work we examine the application error sensor array filtering to simultaneously extract the shear and moment field components which lead to real stuctural power, and drive and adaptive filtered-x algorithm to minimize the resulting structural power radiation. The observed acceleration field in a structure can have many components due to standing waves where the actual propagating wave components are relatively small in amplitude. Weak propagating waves in the presence of strong standing waves is perhaps one of the more salient problems associated with active reduction of structural radiation from heavy fluid-loaded structures.[1] Long wavelength (supersonic wave number) structural vibrations couple well into the fluid and thus cause those structural vibration components to be highly damped relative to the unimportant subsonic vibration. By using an array of accelerometers to extract the shear and moment field components which contribute to real vibration power, one can filter the acceleration components which do not contribute to real power and implement an adaptive filtered-x algorithm for active cancellation of the propagating power in the structure. The bending wave intensity technique has become relatively mature using accelerometer arrays[2,3] as well as using mordern cross-spectral techniques.[4] For active control of the total bending wave power, it has been shown that two control actuators are needed to simultaneously control both the shear and moment forces.[5] The major issue in integrating an intensity error signal into an active vibration control adaptive system is that the error signal used in the adaptive algorithm must be a linear function of the control action on the system. One recent approach, although limited to single narrow-band frequencies, has been experimentally shown effective where the normal product of the error and filtered-x signals in the adaptive filter coefficient updates are replaced with the instantaneous intensity itself.[6] The design approach presented here[7] is to develop an algorithm for broadband structural intensity control using the filtered-x algorithm where one has an independent reference signal coherent with the noise to be canceled. Our design develops a multichannel error accelerometer filter which combines five accelerometer signals to produce a single output signal which is linearly proportional to the bending wave components which constitute real power.

I. FREQUENCY DOMAIN MODEL OF STRUCTURAL INTENSITY

This analytical study is based on a structural steel beam also used by Hayek *et al.*[8] and Schwenk[9] so that the error intensity simultations can be compared to actual experiment for select cases. Of particular interest is the effect of structural near fields on the intensity control performance. The beam has a length L of 1.22 m, excluding an additional 0.3 m length terminated in a bed of dry, loose sand, and a cross-sectional area A of 74 μm^2. The modulus of elasticity E is assumed to be 186.9 GPa, density ρ of 7700 kg/m^3, and moment of inertia I of 2.71 nm^4. The end of the beam near $x=L$ is free and we have a harmonic point force F_0 and position x_0 normal to the beam surface. The termination impedances over the range of frequencies of interest were measured experimentally by Tousi[10] based on measuring the two flexural standing wave ratios. In order to measure the flexural intensity using standard accelerometers, one simply estimates the spatial derivitives using finite difference approximations. In this work we use a five accelerometer array with uniform 4-cm spacing to estimate all the spatial derivitives at the location of the middle, or third, accelerometer. Consider the beam setup as seen in Fig. 1.

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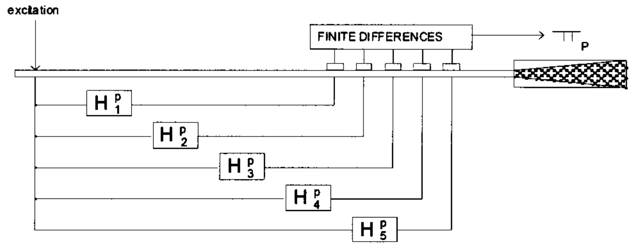

FIG. 1. The transfer function between the intensity output and the force input can be described as a weighted combination of five filters due to the finite difference derivitive approximations.

Applying well-known difference equations, one has the total bending intensity at the position of the middle accelerometer a_3 [dropping the (ω) notation for compactness], as seen in Eq. (1):

$$\Pi_p(\omega) \simeq j \frac{EI}{2\Delta^3 \omega^3} \{[-a_5 + 2a_4 - 2a_2 + a_1] \cdot a_3^* + [a_4 - 2a_3 + a_2] \cdot [a_4^* - a_2^*]\}. \tag{1}$$

Equation (1) is actually nonlinear due to the cross-spectra of accelerations. However, for steady-state or stationary vibration signals small changes in acceleration levels lead to approximately linear changes in intensity level. Since the intensity is expressed as a spectrum, it is already time averaged as well as orthogonal in frequency. Therefore, for stationary signals one can see that the approximate flexural intensity in Eq. (1) has been linearized with respect to the steady-state excitation force. The error spectral response is now simply a weighting function to drive the filtered-x adaptive control algorithm where the phase of the error plant is still included as part of the filtered-x operation on the reference signal.

II. SIMULATION RESULTS

A range of control actuator and error sensor locations was examined to minimize the intensity errors due to the finite difference approximation as well as to examine the near-field and far-field performances of intensity control in general. The spacing between the two control actuators is 10 cm and the spacing between the accelerometers in the intensity array is 4 cm. Figure 2 summarizes the control results

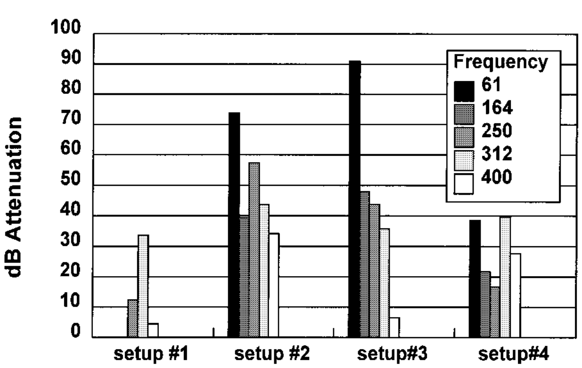

FIG. 2. Setup 3 with the control actuators in the near field of the primary excitation and error sensors in the farfield of the control actuators appears to have the best performance near resonances of the beam.

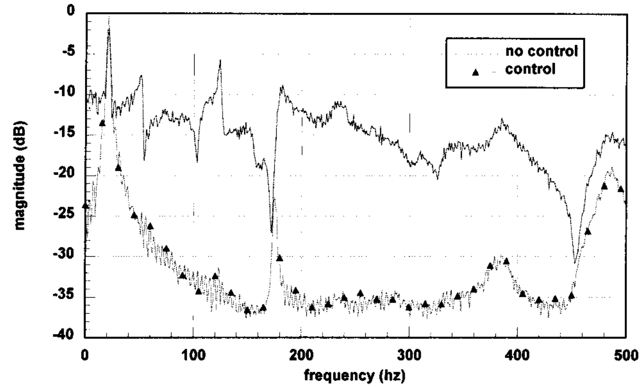

FIG. 3. Broadband control of flexural intensity from random vibrations is possible using the psuedo-intensity error filtering technique and a simple time-domain filtered-x controller.

using the psuedointensity error filtering algorithm for four actuator and error sensor array locations. Since the near-field/far-field boundary is frequency dependent, the beam termination impedance, precise locations of the control actuators and error sensor array is different for each frequency and setup and can be found in Ref. 7. Setups 1 and 2 have the active control sources in the far field of the excitation, but setup 1 has the error in the far field of the control actuators and setup 2 has the error array in the near field of the control actuators. Setups 3 and 4 have the control actuators in the near field of the primary excitation force, but setup 3 has the arror array in the far field and setup 4 in the near field of the control actuators.

Due to the limitations of the model length, one could not place the control actuators in the far field of the primary excitation for setup 1 at the lowest frequencies of 61 and 164 Hz. Both setups 2 and 3 appear to give good overall performance with setup 3 providing the best low frequency results. It is likely that finite difference approximations in the intensity calculation are contributing factors to this performance limit. The main benefit of the intensity error filtering algorithm in the filtered-x adaptive controller[11] is the ability to actively control broadband intensity using a time-domain adaptive control algorithm. The only limitation is that the excitation force should be stationary and ergodic. This allows the measured time-averaged intensity at the error array to be used to construct a filter which passes vibration signal components which are coherent with the propagating flexural intensity. Figure 3 shows the broadband performance simulation results for the intensity active control algorithm. The peaks and dips in the responses are due to the primary and secondary actuator locations on the beam and the resulting modal response as observed at the accelerometer array in the simulation.

III. CONCLUSIONS

A broadband flexural intensity adaptive control algorithm is presented which shows reasonable performance on single-frequency and broadband excitation for active intensity control. The force-to-acceleration transfer functions from point to point in the beam are modeled using the classic Euler–Bernoulli 4th order differential equation for a finite beam. The transfer functions led us to develop a psuedo-intensity filter which essentially linearizes the intensity control problem by providing only the important error signal components which lead to propagating power. It can be seen as a broadband wave vector filter which suppresses the standing wave and near-field components while passing the propagating wave components. This filtering is however, signal dependent, meaning that one must on-line measure the flexural intensity and adaptively design a filter to pass the proper signal components. The single-frequency performance of the psuedo-intensity and linearized intensity gradient algorithms is quite comparible as are the near-field/far-field performances with the experiments of Sommerfeldt.[6,9] It can therefore be seen that the numerical modeling presented here is of reasonable enough accuracy to claim that the psuedo-intensity error filtering approach could be quite useful for the development of real-time steady-state flexural intensity control on finite beams.

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