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EXPERIMENTAL INVESTIGATION OF STRUCTURAL INTENSITY CONTROL IN A VIBRATING PANEL USING A FINITE DIFFERENCING APPROACH

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ABSTRACT

The active reduction of vibrational energy flow by means of structural intensity (SI) proposes to be an effective approach towards global downstream attenuation of a structure based on preliminary numerical studies. This work examines an approach on SI control by finite difference approximation of velocities. Only transversal waves are considered. Different levels of complexity are taken into consideration and compared to a state-of-the-art active vibration control. A feed-forward controller is estimated based on the disturbance force as a reference signal. The controller minimizes the target functions, i.e. different components of SI to evaluate the impact of error sensor array complexity on global reduction. Multiple configurations of control actuators, specifically inertial shakers, are investigated. Targeting additional internal forces benefits in a significantly lower global vibration level downstream of the error sensor positions, whilst using a less dense array of sensors with respect to wavelength of the sound. Implementing internal forces up to third order of spatial derivatives (shear forces) perform worse than a simple approach with additional angular velocity, as sensing errors amplify non-linearly.

Keywords: *structural intensity, active control, flexural waves*

1. INTRODUCTION

To reduce the overall noise level caused by discrete sources of noise and vibration, the attenuation of the latter poses the trivial solution. Naturally, this is not possible in many cases. Hence, the vibration are conducted to different parts of the structure, leading to noise emission by radiating surfaces. Several approaches are well known to reduce local or global sound pressure levels. However, common limitations are either the addition of weight, and effectiveness in only higher frequency bands (as for most passive approaches) or a rather complex set-up and distribution of sensors and actuators for a global attenuation in a given cavity for active approaches. Here, another approach was proposed in previous publications [1, 2]: The reduction of energy transmission from vibration sources to relevant radiating surfaces. A simple example would be the vibration caused by aircraft engines, especially configurations with tail mounted open rotors. The structure-borne part of vibration is transferred to the cabin, leading to uncomfortable noise levels. To reduce the noise level globally, the entire cabin needs to be instrumented with sensors and actuators. This instrumentation could be simplified, if the active system was limited to the transfer paths of vibration, i.e. actively blocking the energy transmission. The structural intensity poses to be a fitting target function for this.

The measurement of structural intensity started in the 1970s with the works of Noiseux [3] and Pavić [4], followed by different approaches towards its active control [5–7]. This work deals with the comparison of known control approaches as well as possible simplifications on an experimental set-up based on numerical pre-studies in [2, 8].

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2. EXPERIMENTAL SET-UP

The experiments are conducted on an aluminum plate of rectangular shape with constant thickness. The plate is suspended by rubber bands in a vertical position. An electro-dynamic shaker (LDS V201) is used to generate a disturbance vibration. Eight inertial shakers (Visaton EX45s) are taped to the plate in a two-by-four grid to allow different sets of secondary excitation. The overall structural vibration as well as the error sensor responses are measures using a Polytec OFV 055 Laser Scanning Vibrometer referencing the excitation voltages of the respective shakers. Fig. 1 shows the dimensions and positioning of actuators and sensor arrays of the experimental set-up.

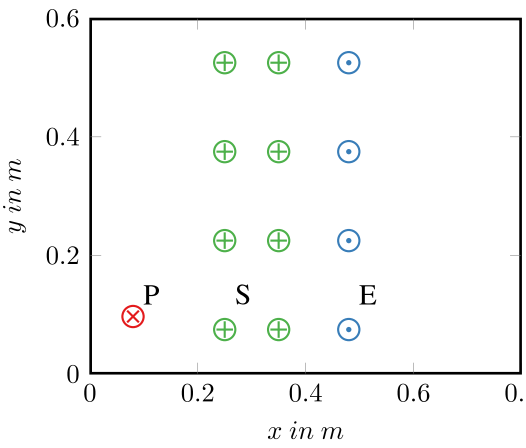

Figure 1. Dimensions and positioning of experimental set-up: Rectangular aluminum plate, P primary normal force, S secondary normal forces, E positions of error sensor array center node

Each error sensor position is equipped with an array of 13 scanning points returning the frequency response of the normal velocity to the aforementioned reference excitation voltage. These 13 points are positioned according to Fig. 2 to allow finite differencing up to the third spatial order in x and y direction. Based on Kirchhoff-Love equations, internal forces can be approximated by finite differences of different orders assuming an equidistant sensor spacing with known distance and the knowledge of plate bending stiffness. The derivations of the formulae for approximating the internal measures is already examined in [1]. For the sensor spacing Δ a distance of $20\,\mathrm{mm}$ was used based on preliminary studies on the influence of sensor distance on approximation accuracy and error sensitivity.

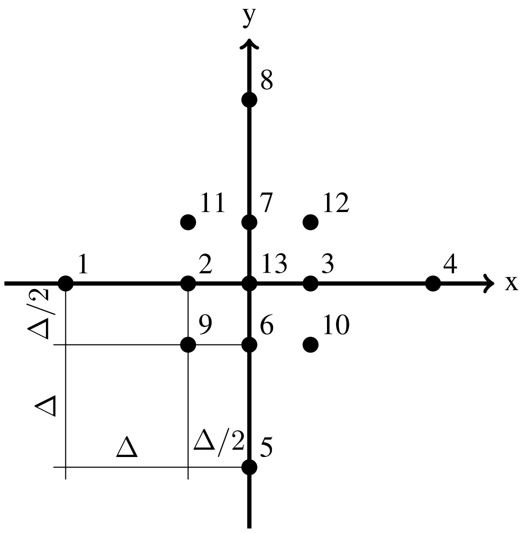

Figure 2. Velocity sensor array for approximating SI components by finite differences: 13 velocity query points, $\Delta = 20\,\mathrm{mm}$

Tab. 1 shows the signal processing parameters for the estimation of transfer paths from the reference signal to the velocity responses by each shaker.

Table 1. Signal processing parameters for the estimation of transfer paths

sampling frequency	$2.56\,\mathrm{kHz}$
frequency resolution	$0.625\,\mathrm{Hz}$
maximum frequency	$1\,\mathrm{kHz}$
averaging	3 x complex
reference signal	pseudo-random noise @ $1\,\mathrm{V}$

3. CONTROL APPROACH

As proposed, structural intensity is (indirectly) used as the target function for the control. Structural intensity is basically the structure-borne equivalent of acoustic or sound intensity. It is defined by the vibrational energy transmitted through a section of the structure. In this work, only flexural waves are taken into consideration. By assuming the kinematic conditions of Kirchhoff-Love for plates, the structural intensity can be defined by the following equation [4]:

$$SI_x = (Q_x \cdot \dot{\eta} + M_{xx} \cdot \omega_x + M_{xy} \cdot \omega_y) \cdot A^{-1} \qquad (1)$$

The structural intensity in direction x is defined by the sum of the products of shear force Q_x and normal velocity $\dot{\eta}$, bending moment M_{xy} and angular velocity ω_y and twisting moment M_{xx} and angular velocity ω_x, all referenced to the cross-section A as depicted in Fig. 3.

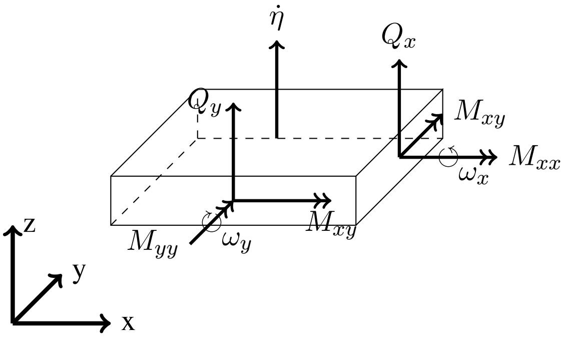

Figure 3. Coordinate system and measures of positive influence line of a plate element: Shear force Q_x, normal velocity $\dot{\eta}$, bending moment M_{xy}, twisting moment M_{xx} and angular velocities ω_y and ω_y

To actively reduce structural intensity, a linear feed-forward controller is used. The control loop is shown in Fig. 4. To assume linearity between the reference signal (i.e. the excitation voltage of a shaker) and the target function, the components of structural intensity, i.e. shear force, moments, velocities, are used (hence, the term indirectly) in different combinations. The filters for each combination are calculated offline. Therefore, the primary signals Sig_{Prim} and secondary signals Sig_{scnd} are calculated using the estimated transfer functions and a generated tonal reference signal. An optimal Wiener filter W is then estimated in order to minimize the difference between the primary and secondary signals. By then inverting the input of the filtered reference signal, the secondary signal should eliminate the primary signal to a certain extent.

Tab. 2 shows a summary of the combinations of control target functions. Two combinations -PAVIC2D and PAVIC1D- are based on the full approximation of internal forces, whilst the latter omits mixed spatial derivatives, i.e. assuming a beam-like structure. Two other combinations refer to the investigation of Noiseux [3], meaning shear force and moment component of SI are equal (in the far field). In these two cases, the shear force is not taken as a control target. The suffices 2D and 1D refer to the approximation of the moments with or without mixed spatial derivatives, as in the PAVIC combinations, respectively. Consequently, the simplest combination is described by VELOMG, only using the normal velocity and angular velocities as control target. This is based on

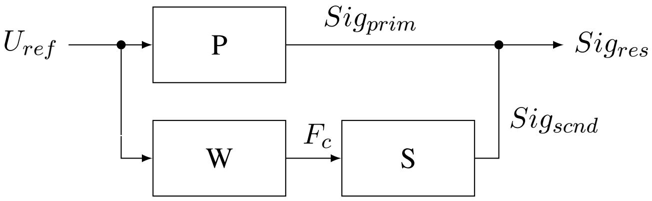

Figure 4. Scheme for feed-forward SI component controller: Reference signal U_{ref}, P primary and S secondary path from reference to SI components Sig_{prim} and Sig_{scnd}, W feed-forward filter, F_c filtered reference signal for secondary actuator input, Sig_{res} sum of primary and secondary SI components

Table 2. Assumptions and required number of sensors per array for SI approximation methods

PAVIC2D	common Kirchhoff plate	13 sensors
PAVIC1D	Timoshenko beam	9 sensors
NOISEUX2D	PAVIC2D, w/o shear force	9 sensors
NOISEUX1D	PAVIC1D, w/o shear force	5 sensors
VELOMG	velocity and angular velocity	5 sensors
VEL	velocity	1 sensor
VELX	velocity	5 sensors

the idea to only minimize one factor of each summand of Eqn. 1. To compare the SI control to a simpler velocity control, two set-ups with a single sensor (VEL) and five sensors (VELX) per array are taken into account.

4. RESULTS

To investigate the controller performance for different operational shapes, the filters were calculated for selected mono-tonal excitation first. For each frequency, a set of error sensor positions and secondary actuators was selected. In this study, two configurations for error sensors were taken into account (only two positions vs. all four positions) as well as two configurations for the secondary forces (four secondary shakers at $x = 0.25m$ vs. all secondary shakers). These configurations were selected in order to investigate the impact of error sensor density as well as the importance of the use of force pairs in comparison to single forces (with respect to x direction).

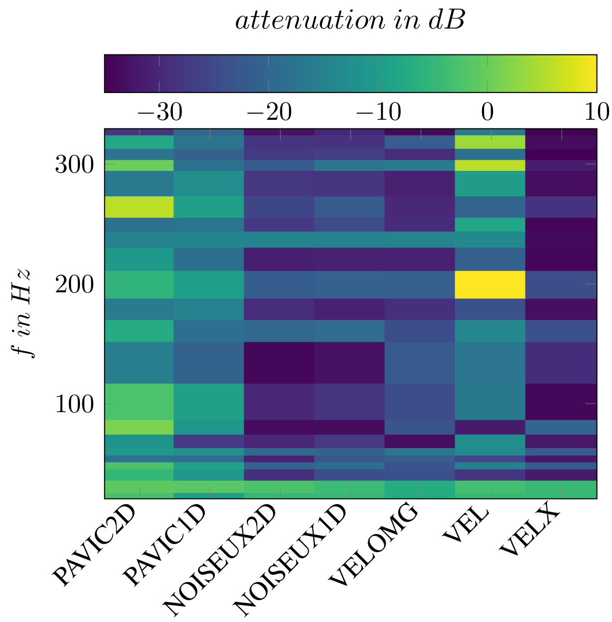

Figure 5. Downstream reduction of quadratic sum of velocity with two parallel lines of secondary shakers, four equidistant error positions and mono-tonal excitation

Fig. 5 to 9 show the reduction of plate vibration by means of summed quadratic velocity amplitudes of the measuring points from $x > 0.48\,\mathrm{m}$, i.e. downstream of the error sensor center position. This area is used to estimate the barrier effect of the investigated methods. An estimation of structural intensity for the entire downstream area would require a large effort on FE model updating or a significantly larger set of scanning points. Therefore, the quadratic velocities (being proportional to kinetic energy) is used to evaluate the resulting attenuation. Each figure shows the reduction for a specific set-up of error sensors and secondary shakers as described before. A selection of frequencies was investigated by estimating controllers for resonant and anti-resonant mono-tonal excitation.

Fig. 5 shows the attenuation using two parallel lines of secondary shakers with four error sensor arrays. As expected from pre-studies [2, 8], implementing third order spatial derivatives, i.e. the approximation of shear forces PAVIC1D and PAVIC2D, performs worse than simplified methods. Reduction can be achieved, however, probable misplacement of sensor points and consecutive deviation of sensor spacing within the array lead to an amplified error with order 3, especially disturbing phase information of the to be controlled shear force signal. This issue can be seen through all frequencies, especially in anti-resonant excitation due to the low signal to noise ratio.

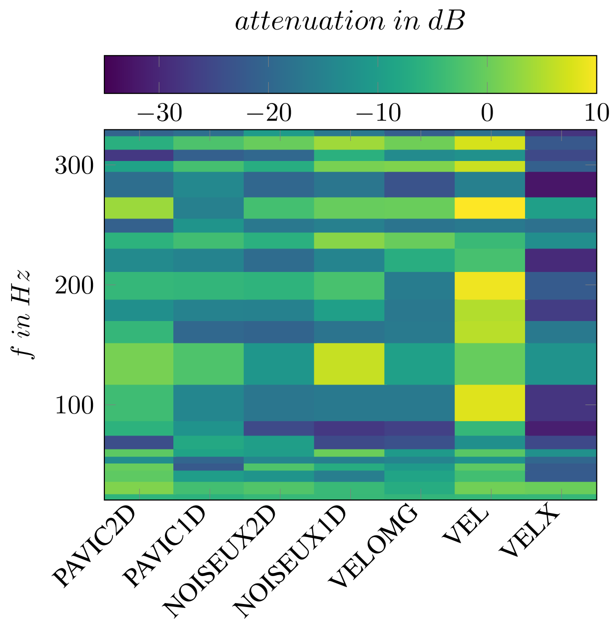

Figure 6. Downstream reduction of quadratic sum of velocity with two parallel lines of secondary shakers, two equidistant error positions and mono-tonal excitation

The first stage of simplified approximation, NOISEUX1D and NOISEUX2D, perform significantly better. Here, the shear force was omitted, hence only targeting moments, velocity and angular velocity. Only targeting velocity and angular velocity and additionally omitting moments, however, achieves a comparable reduction of downstream vibration levels. Hence, for this set-up, a significantly simpler sensor set-up shows the best performance in comparison to complexity.

A comparison to both velocity control methods shows, that a single sensor per error position is not sufficient to reduce overall downstream vibration. Thus, using five velocity signals achieves comparable or even better results compared to velocity plus angular velocity.

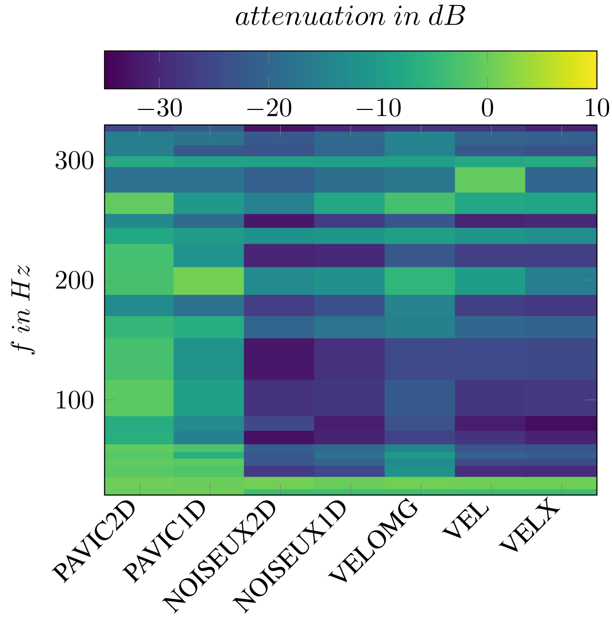

Figure 7. Downstream reduction of quadratic sum of velocity with single line of secondary shakers, four equidistant error positions and mono-tonal excitation

Fig. 6 and Fig. 8 show attenuation for only two error positions. Regarding the density of error sensors it becomes apparent, that a higher density yields a greater global vibration reduction for all methods. Secondly, for this set-up, however, the implementation of force pairs in contrast to a single line of actuators achieves no greater reduction, as shown in Fig. 7 and Fig. 8.

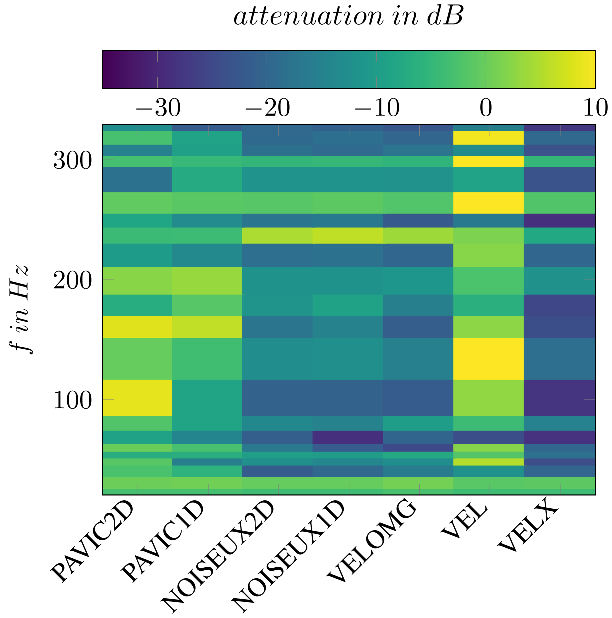

Figure 8. Downstream reduction of quadratic sum of velocity with single line of secondary shakers, two equidistant error positions and mono-tonal excitation

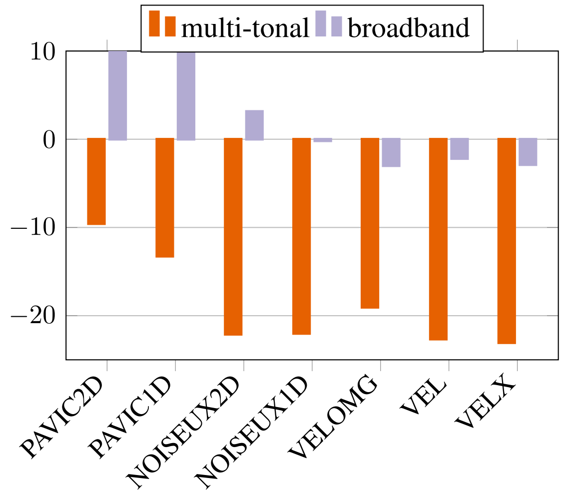

Figure 9. Downstream reduction of quadratic sum of velocity with two parallel lines of secondary shakers, four equidistant error positions and multi-tonal and broadband (1 Hz to 500 Hz) excitation

Examining more complex excitation, a benefit of the velocity plus angular velocity method can be shown for a broadband excitation, as depicted in Fig. 9. The PAVIC as well as NOISEUX methods do not achieve any reduction or even a significant amplification. Using multiple velocity sensors, however, is only slightly less performant. For the multi-tonal excitation with four simultaneous excitation frequencies, the results are comparable to the monotonal case.

5. SUMMARY

Considering the performance of structural intensity based methods for vibration reduction, the numerical pre-studies in [2, 8] could partly be confirmed. As expected, methods considering third order spatial derivatives lack robustness and cause estimation errors due to higher sensitivity in sensor placement. Omitting these derivatives in a first approach on simplification drastically improves controller performance. Thus, a comparable reduction in downstream vibration can also be achieved by even omitting second order derivatives, too. The experiments show, that a significantly better vibration reduction can be achieved by including multiple sensor points for velocity control in an array shape, with either controlling first order derivatives, i.e. angular velocities, or multiple velocities.

This study dealt with a simple unstiffened panel. Further investigation will be done on stiffened as well as inhomogeneously damped structures in order to estimate controller performance for traveling waves and more complex geometries ans transfer paths. In these cases, numerical assessment promises to show better results for structural intensity based methods compared to velocity set-ups. Issues with sensor placement errors will also be examined in further research by implementing strain gauges, enabling the measurement of higher order spatial derivatives for plates directly.

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