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Design of damping layout using spatial-damping identification methods

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ABSTRACT

The design of a damping layout can result in a frequency-focused reduction of vibration responses. Theoretical approaches that relate the spatial-damping parameters with the frequency content of the damping are limited. This research introduces a theoretical approach to damping-layout design (location and size) with frequency-content control. Initially, the frequency-response functions (measured or simulated) are modified to obtain the required damping layout via spatial-damping identification methods. The use of these methods provides a straightforward relationship between the frequency responses and the targeted spatial damping. The Lee–Kim spatial-damping identification method is used in the presented numerical and experimental case studies. The numerical and experimental results show that the approach is capable of providing the desired frequency content. This approach can be a valuable tool for a damping-layout assessment as high damping can be achieved with a reduced amount of damping material in a single-step solution.

1. Introduction

Damping is the dissipation of mechanical energy, mostly in the form of heat and, to a lesser extent, as acoustic radiation, transmission to coupled dynamic systems or other forms of dissipation [1]. In structural dynamics, damping, combined with mass and stiffness, represents the dynamic properties of a structure and is important for the validation and building of analytical/numerical models in civil, mechanical and aerospace engineering [2,3]. In these industries, a number of structures are treated with damping materials to reduce the amount of structure-borne noise [4], to decrease vibration levels [1] or to increase fatigue life [5]. The industrial use of a damping treatment demands its optimization for reasons such as the cost-effectiveness and the mass loading of the structure. The result of this optimization approach should be the configuration of the damping layout with the minimum use of damping material – in short, its minimum spatial layout.

The standard approach to identifying damping in linear mechanical systems is to use one of the following methods: logarithmic decay [6] in the time domain, a continuous wavelet transform [7], the Morlet wave method [8] or the synchrosqueezed wavelet [9] in the time-frequency domain, or half-power point [6] and circle fit [6] in the frequency domain. It is also possible to evaluate the internal damping using macroscopic constitutive models [10]. However, these damping-identification methods do not provide any spatial information (i.e., the damping distribution throughout the structure).

For spatial damping, direct-damping identification methods were developed that identify the spatial damping directly from the frequency response functions (FRFs) without a transformation to the modal coordinates. Lee and Kim presented the dynamic-stiffness method [11], which identifies the damping separately from the mass and stiffness based on the imaginary and the real properties of the FRF. Other spatial-damping identification methods, not considered in this research, are reviewed in [12–17].

Spatial-damping optimization approaches can be divided into the experimental and analytical [4]. The experimental approaches normally use laser vibrometry to map the vibration responses at several locations. These responses are subsequently examined and then the damping is applied to selected regions [1]. It is important to excite the structure over a wide frequency range in order to identify all the noise and transfer paths [4], which can be a time-consuming operation. On the other hand, the analytical approach consists of maximizing the damping or minimizing the structural responses by changing the numerical/analytical model parameters within the given constraints. The advantage of the analytical approach over the experimental approach is that it can be applied during the early stages of the design, but it is usually calculation-intensive and requires a detailed structural model (e.g., a large FEM model). There are a number of less general, spatial-damping optimization methods that are geometry- or material-specific (e.g., for plates [18,23], shells [19], composite materials [20]). General

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material can be implemented into the FEM-based method [21,22], but the result is a damping layout of variable thickness fragmented over the structure that is not very practical to implement.

In contrast to the optimization methods where typically the mass volume of the damping material is minimized, this research focuses on damping design for frequency-focused vibration reduction. The underlying idea is to use one of the existing spatial-damping identification methods that gives a straightforward relationship between the frequency responses and the targeted spatial damping.

This research is organized as follows. The damping-layout design approach is introduced in Section 2. In Section 3, the theoretical background of the Lee-Kim method is briefly presented. In Section 4, the validation of the approach is illustrated with two numerical examples and later the performance of the approach is tested with a real beam experiment. Finally, the conclusions are drawn in Section 5.

2. Design of damping layout

A frequency-domain design approach is presented here in which the frequency-response functions (FRFs) are modified and the resulting changes in amplitudes are estimated using established spatial-damping identification methods. Fig. 1 shows the required steps. The input data is the measured (or synthesized) FRF matrix $\mathbf{H}(\omega)$, after which the modal damping ratios are changed in the frequency domain to obtain the modified FRF matrix $\mathbf{H}_{\mathrm{MOD}}(\omega)$. The spatial-damping identification method is applied to both FRF matrices to obtain the initial $\mathbf{D}_{\mathrm{INIT}}$ and modified $\mathbf{D}_{\mathrm{MOD}}$ spatial-damping matrices. The difference between the spatial-damping matrices is the damping layout.

The input data $\mathbf{H}(\omega)$ can be synthesized from the spatial model [6]:

$$\mathbf{H}(\omega) = \left[\mathbf{K} - \omega^2\mathbf{M} + \mathrm{i}\mathbf{D}\right]^{-1} \tag{1}$$

where $\mathbf{K}$ is the stiffness matrix, $\mathbf{M}$ is the mass matrix, $\mathbf{D}$ is the hysteretic damping matrix and ω is the angular frequency. The second option is to synthesize $\mathbf{H}(\omega)$ from the modal data. The FRF matrix is synthesized for each coordinate j and k as the sum over n modes as [6]:

$$\mathbf{H}_{jk}(\omega) = \sum_{r=1}^{n} \frac{{}_rA_{j,k}}{(1+\mathrm{i}\eta_r)\omega_r^2 - \omega^2} \tag{2}$$

where r is the mode number, ${}_rA_{j,r}$ is the modal constant of the r-th mode for the matrix coordinates j and k, ω_r is the eigenfrequency of the r-th mode and η_r is the damping ratio of the r-th mode.

After obtaining the initial FRFs, the damping ratios of the selected modes are changed to obtain the desired frequency content, see Fig. 2. Regardless of the input data (e.g., measured or synthesized) the modal parameters of the initial FRF matrix can be extracted using experimental modal analysis (EMA) [6]. The mode-based approach to obtaining the desired frequency content is preferred because the vibration responses are sensitive to the damping changes for the frequency range around the resonances only [1]. From the modified modal parameters (i.e., the damping ratio changes) the modified FRF matrix is reconstructed with (2).

Finally, the spatial-damping identification method is used to identify the spatial-damping matrices from both FRF matrices. The identified spatial-damping matrix is the spatial distribution of the damping over the structure and the difference between the initial and modified damping matrices is the required damping layout.

The proposed spatial-damping design approach can be developed into an iterative one to account for the mass and stiffness

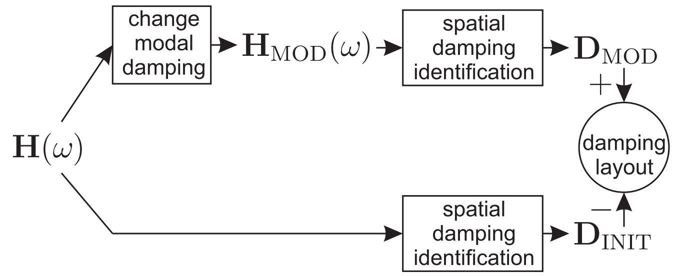

Fig. 1. Proposed damping-layout design approach.

changes of the applied damping treatment [23], but its development is beyond the scope of this research.

The Lee–Kim [11] spatial-damping identification method will be used in the case studies. The method is general and can be applied to any type of structure; its performance was thoroughly analysed in [24]. A theoretical presentation of the method is given next.

3. Spatial-damping identification method

In this section the background of the Lee–Kim [11] direct-damping identification method for hysteretic damping is briefly presented. Assuming a linear system and a harmonic excitation/response, the general, second-order, matrix differential equation can be written in the frequency domain as [6]:

$$\left[\mathbf{K} - \omega^2\mathbf{M} + \mathrm{i}\mathbf{D}\right]\boldsymbol{X}(\omega) = \boldsymbol{F}(\omega) \tag{3}$$

From (3), the receptance FRF matrix $\mathbf{H}(\omega)$ is defined as [6]:

$$\boldsymbol{X}(\omega) = \left[\mathbf{K} - \omega^2\mathbf{M} + \mathrm{i}\mathbf{D}\right]^{-1}\boldsymbol{F}(\omega) = \mathbf{H}(\omega)\boldsymbol{F}(\omega) \tag{4}$$

and the dynamic stiffness matrix $\mathbf{Z}(\omega)$ is defined as the matrix inverse of $\mathbf{H}(\omega)$ at each frequency point ω:

$$\mathbf{Z}(\omega) = \mathbf{H}(\omega)^{-1} = \left[\mathbf{K} - \omega^2\mathbf{M} + \mathrm{i}\mathbf{D}\right] \tag{5}$$

Using (5) the hysteretic damping matrix might be obtained directly from the imaginary part of the dynamic stiffness matrix $\mathbf{Z}(\omega)$:

$$\mathrm{imag}(\mathbf{Z}(\omega)) = \mathrm{imag}([\mathbf{H}(\omega)]^{-1}) = \mathbf{D}, \tag{6}$$

Rearranging (6) to isolate the damping matrix $\mathbf{D}$ gives:

$$\mathbf{D} = \mathrm{imag}([\mathbf{H}(\omega)]^{-1}) \tag{7}$$

Method (7) is not limited to hysteretic damping [25].

4. Numerical 5 DoF case study

Fig. 3 represents a 5-degree-of-freedom (DoF) lumped-mass model that will be used for the initial validation of the proposed method. Two model properties are defined by the mass $m = 5$ kg and the stiffness $k = 2{\cdot}10^6$ N/m, and are arranged into mass $\mathbf{M}$ and stiffness $\mathbf{K}$ matrices. The initial hysteretic spatial-damping values d of the model are defined as the stiffness-proportional damping [6] at the matrix level as:

$$\mathbf{D} = \beta\mathbf{K}, \tag{8}$$

where β is the stiffness proportional constant, which was chosen to be 0.01.