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Experimental direct spatial damping identification by the Stabilised Layers Method

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ABSTRACT

A new method is developed for direct damping matrix identification using experimental receptance-matrix data together with physical connectivity constraints based on what are described as *layers*. A number of spectral lines are considered in symmetric frequency bands around the damped peaks of the receptances and the identification procedure is shown to be ill-conditioned (singular) when one of the spectral lines coincides with an undamped natural frequency. A test is developed that makes use of a stabilisation diagram to ensure not only that a solution exists, but also that it is stable when the number and frequency range of the spectral lines is changed. An experimental parametric three degrees of freedom lumped mass system connected by springs and air dampers is considered and the matrix of non-proportional viscous damping terms is identified under different damper configurations and levels.

1. Introduction

The exact identification, localisation and quantification of dissipation sources in mechanical system remain as unsolved problems. While inertial and elastic properties of mechanical system are well understood, damping properties remain obscure and are often modelled equivalently so that the mechanism of energy dissipation is unrepresentative of the true physics. Better understanding the spatial distribution of dissipation sources is therefore a desirable objective and potentially very useful design tool to improve the efficiency of many mechanical systems, especially in problems of Noise Vibration and Harshness (NVH). The commonly used and most simple equivalent model is the famous Lord Rayleigh proportional viscous damping model, which relates the dissipation in a structure only to the velocity field. This model is a particular case of the more general Rayleigh dissipation function [1]. The proportional viscous damping model simplifies the modal analysis to the solution of a strictly real eigenvalue problem. A system can be defined as proportionally damped if the system matrices satisfy the relation $\mathbf{KM}^{-1}\mathbf{C} = \mathbf{CM}^{-1}\mathbf{K}$ [2,3], in which $\mathbf{M} = \mathbf{M}^T$ is the system mass matrix, $\mathbf{C} = \mathbf{C}^T$ is the viscous damping matrix, $\mathbf{K} = \mathbf{K}^T$ is the stiffness matrix and $\mathbf{M}, \mathbf{C}, \mathbf{K} \in \Re^{n \times n}$. The proportional viscous damping model, while mathematically convenient, quite rarely represents the true nature of dissipation in a system. Numerous damping theories were developed to represent dissipation in mechanical systems and Adhikari and Woodhouse [4] gave an extensive review of the non-viscous models. Non-proportional viscous damping models are regularly used in earthquake response analysis problems and in coupled systems such as classical aerospace fluid-structure interactions and in assembled, combined or hybrid structures [5].

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The identification of a general viscous damping matrix is problem fraught with complications. Several classes of identification method can be found in literature, including Lancaster's formula, energy-based methods, first order perturbation analysis [6], the instrumented variables and local equation of motion methods [7], which appear to be the most widely used. Prandina et al. (2009) [6] and Brumat et al. (2016) [7] produced good identification results when using the inverse receptance method. The effect of modal truncation was investigated in Ref. [6] while in Ref. [7] the local equation of motion method was found to locate damping sources precisely only for simple continuous structures when the analytical equation of motion was known, such as for beams or plates. Arora [8] presented a method for structural damping identification from direct experimental frequency response functions (FRFs) and in Ref. [9] a new structural damping matrix updating method in two steps. Both methods used the concept of the equivalent frequency response function of the undamped system introduced by Chen et al. [10]. In Ref. [11] Chen et al. presented a method based on the inverse undamped receptance matrix, derived from the experimental complex receptance matrix, to directly identify the viscous damping matrix from experimental FRFs. The method was extended by Lee and Kim [12,13] to structural damping, so that both viscous and structural damping matrices were identified directly from the imaginary part of the inverse receptance matrix. With all these identification methods, it is possible to obtain physically meaningless results, because no constraints (except on symmetry) are imposed upon the solution. This can result in the identification of not only wrongly located damping elements, but also unstable ones.

In damping identification, the user regularly encounters problems of non-uniqueness because of the many equivalent damping matrices that can represent the system response equally well [14]. The layers method, proposed by the authors [15], overcomes this problem by adding topological constraints to the identification with the purpose of finding the solution closest to the system real topology. The constraints are based on the system physical structure: if the system is known to be stable, all the elementary dampers should be also locally stable, moreover only degrees of freedom physically linked can have damping between them. Chen's method [10,11] combined with the layers method was applied for the identification of viscous and structural damping for a body-in-white car chassis [15]; the results were computed using FRF values at the chassis natural frequencies, where it is known the damping has the greatest effect on elastic modes [4]. The layers approach reduced drastically the number of unknowns in Chen's method and provided reliable results.

The aim of this paper is to validate the Stabilised Layers Method (SLM) on a simpler system, much more controllable than an automotive body in white chassis. In the chassis example [15] it is seen how the method gives realistic spatial damping distribution, but the quantification of shock absorbers damping coefficients can only be validated against datasheet values. In this work identified damping spatial distribution and quantification can be validated by comparing them with known damping locations and coefficients. The robustness of the method is proved by changing the frequency ranges in which the identification procedure is performed and the number of spectral lines within the defined ranges. A stabilisation diagram is introduced for the identification procedure. The stabilisation diagram is typical of several identification techniques in different fields, the most common one is the stabilisation diagram for pole identification in vibrating systems [16,17]. In pole identification the model order is successively increased to identify the stable identification of the poles. The same concept is here applied for damper coefficients identification, stabilising the results with respect to both frequency range and numbers of spectral lines.

The paper is organised as follow: in § 2 the parametric experimental setup of the test rig is presented. The basic concept of the layers approach, its integration with the Chen-Ju-Tsuei method and the proposed stabilisation diagram for viscous damping matrix identification are explained and discussed in §3–5. The results of experimental damping localisation and quantification on the test rig are shown in §6. Finally considerations on the presented method and practical suggestions for its application are given in the conclusions.

2. Experimental setup

The test rig is a three degrees of freedom lumped mass-damper-spring system with plate-like springs, shown in Fig. 1. Each mass is connected to the ground through a “ground spring” and linked with its nearest neighbour through a “coupling spring”.

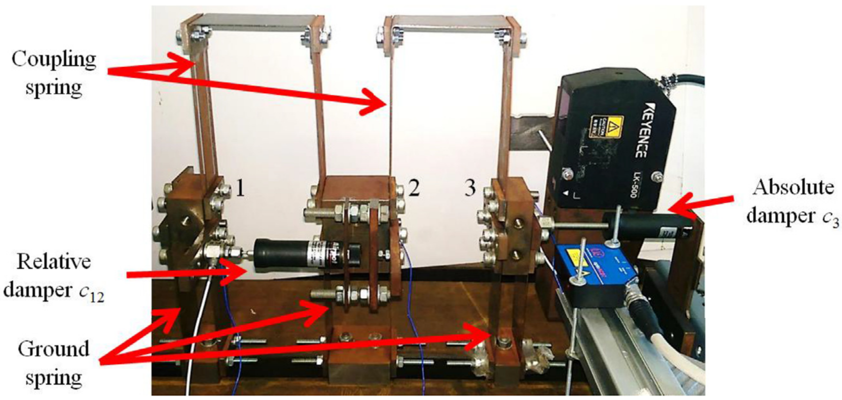

Fig. 1. Three degrees of freedom parametrically damped test rig.