International Journal of Solids and Structures 51 (2014) 133–143

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Structural damping identification method using normal FRFs

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ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form 15 September 2013
Available online 27 September 2013

Keywords:
Damping identification
Direct method
Structural damping
Normal FRFs

ABSTRACT

All structures exhibit some form of damping, but despite a large literature on the damping, it still remains one of the least well-understood aspects of general vibration analysis. The synthesis of damping in structural systems and machines is extremely important if a model is to be used in predicting vibration levels, transient responses, transmissibility, decay times or other characteristics in design and analysis that are dominated by energy dissipation. In this paper, new structural damping identification method using normal frequency response functions (NFRFs) which are obtained experimentally is proposed and tested with the objective that the damped finite element model is able to predict the measured FRFs accurately. The proposed structural damping identification is a direct method. In the proposed method, normal FRFs are estimated from the complex FRFs, which are obtained experimentally of the structure. The estimated normal FRFs are subsequently used for identification of general structural damping. The effectiveness of the proposed structural damping identification method is demonstrated by two numerical simulated examples and one real experimental data. Firstly, a study is performed using a lumped mass system. The lumped mass system study is followed by case involving numerical simulation of fixed–fixed beam. The effect of coordinate incompleteness and robustness of method under presence of noise is investigated. The performance of the proposed structural damping identification method is investigated for cases of light, medium, heavily and non-proportional damped structures. The numerical studies are followed by a case involving actual measured data for the case of a cantilever beam structure. The results have shown that the proposed damping identification method can be used to derive an accurate general structural damping model of the system. This is illustrated by matching the damped identified FRFs with the experimentally obtained FRFs.

1. Introduction

The modeling of damping is a very complex and still considered somewhat an unknown or grey area. The effects of damping are clear, but the characterization of damping is a puzzle waiting to be solved. A major reason for this is that, in contrast with inertia and stiffness forces, it is not clear which state variables are relevant to determine the damping forces. A commonly used model originated by Lord Rayleigh (1897) assumes that instantaneous generalized velocities are the only variables. The Taylor expansion then leads to a model, which encapsulates damping behavior in a dissipation matrix, directly analogous to the mass and stiffness matrices. However, it is important to avoid the misconception that, this is the only model of vibration damping. It is possible for the damping forces to depend upon values of other quantities. Any model, which guarantees that the energy dissipation rate is non-negative, can be a potential candidate to represent the damping of a given structure. The appropriate choice of damping model depends of course on the detailed mechanisms of damping. Unfortunately these mechanisms are more varied and less well-understood than the physical mechanisms governing the stiffness and inertia. In broad terms, damping mechanisms can be divided into three classes:

1. Energy dissipated throughout the bulk material making up the structure which is also called as material damping.
2. Dissipation of energy associated with junctions or interfaces between parts of the structure, generally called as boundary damping.
3. Dissipation of energy associated with a fluid in contact with the structure which is also called as viscous damping.

Material damping can arise from variety of micro structural mechanisms (Bert, 1973) but for small strains it is often adequate to represent it through an equivalent linear, visco-elastic continuum model of the material. Damping can then be taken into account via the viscoelastic correspondence principle, which leads to the concept of complex moduli. Boundary damping is less easy to model than material or viscous damping but it is of crucial

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http://dx.doi.org/10.1016/j.ijsolstr.2013.09.017

importance in most of engineering structures. When damping is measured on a built structure, it is commonly found out to be at least an order of magnitude higher than the intrinsic material damping of the main components of the structure. This difference is attributed to effects such as frictional micro-slipping at joints and the air pumping in riveted seams. In such a system the energy loss mechanism would no doubt be significantly non-linear if examined in detail. But it can be considered linear provided it is small. This issue is discussed in detail by Heckl (1962) assuming small damping. He found that linear theory produce acceptable response predictions for panels whose damping mechanism arose from a bolted joint on beam. Oliveto and Greco (2002) conducted a study on how the modal damping ratios change with different boundary conditions and found that Rayleigh-type damping is actually independent of the boundary conditions and modal damping ratios can be easily converted from one boundary condition to another. When a structure exhibits a damped dynamic behavior that does not conform to the classical and well known viscous or hysteric damping models, such problems are addressed by means of fractional derivatives leading to a model in terms of general damping parameters. Maia et al. (1998) discussed the use of fractional damping concept for the modeling the dynamic behavior of the linear systems and showed how this concept allows for clearer interpretation and explanation of the behavior displayed by common viscous and hysteric damping models. Agrawal and Yuan (2002) modeled the damping forces proportional to the fractional derivative of displacements and the fractional differential equations governing the dynamics of a system. Adhikari and Woodhouse (2003) developed four indices to quantify non-viscous damping in discrete linear system. Two of these indices are based on non-viscous damping while third one is based on the residue matrices of the system transfer function and the fourth is based on measured complex modes of the system. Damping identification has important applications in many engineering fields such as modal analysis, condition monitoring and structural dynamic modifications. Chen et al. (1996) presented a method for getting the spatial model from complex frequency response function. Unfortunately, it is unrealistic to assume that all pertinent information is given to solve for damping matrix. Actually, data from testing is neither complete nor error free. Minas and Inman (1991) proposed a method which assumes that analytical mass and stiffness matrices are determined a priori from a finite element model. Eigenvalues and eigenvectors are obtained experimentally, and are allowed to be incomplete, as would be expected from modal testing. The mass and stiffness matrices are reduced to the size of the modal data available. The identified damping matrix is assumed to be real, symmetric and positive definite. The structure must exhibit complex modes for this procedure and the solution is limited to real symmetric positive definite damping matrices. Beliveau (1976) uses natural frequencies, damping ratios, mode shapes and phase angles to identify parameters of viscous damping matrix. The identification is performed iteratively. The mass and stiffness matrices are reduced to the size of the modal data available. This method involves solving an nth order system of linear equations for each eigenvector, making it fairly inefficient. Lancaster (1961) proposed a method of identifying the mass, stiffness and damping matrices of a system directly given only the eigenvalues and eigenvectors. The input data must be normalized in a very specific way for the method to work. The mass and damping matrices to be used to normalize the eigenvectors, which are subsequently used to calculate the damping matrix. This method is only for calculating the viscous damping and Lancaster concludes by stating "the theory is there, should the experimental techniques ever become available. It is still not possible to measure the normalized eigenvectors". The shortfall of this method comes in normalizing the eigenvectors, which requires knowledge of the very same damping matrix which we wish to, find in the end. Pilkey (1998) proposed two methods for computing the viscous damping matrix using complex modal data. The first method is an iterative method which requires prior knowledge of the mass matrix and eigenvalues and eigenvectors. The second method requires more information but less computationally intensive. This method requires prior knowledge of the mass and stiffness matrices and eigendata. Both the methods developed from the Lancaster (1961) concept. Friswell et al. (1998a) proposed a direct method of viscous damping identification using complex modal data. Oho et al. (1990) proposed a method of identifying experimental set of spatial matrices valid only for the hysterical damping for the entire frequency range of interest using FRFs. Using this method, it is possible to set the number of degrees of freedom much larger than the number of resonant frequencies located inside the frequency range of interest and spatial matrices identified are able to represent the dynamic characteristics of the structure under arbitrary boundary conditions even though the conditions differ from those in place at the time of the identification. The limitation of this method is that it is unable to predict correctly in the modal domain. Lee and Kim (2001) proposed an algorithm for the identification of the damping matrices which identifies the viscous and structural damping matrices of the equation of motion of a dynamic system using frequency response matrix. The accuracy of the identified damping matrices depends almost entirely on the accuracy of the measured FRFs, especially their phase angles. Adhikari and Woodhouse (2000a) identified the damping of the system as viscous damping. Most of the above damping identification methods are based on viscous damping model and require the complex modal data, which is obtained using modal analysis of complex FRF. Adhikari and Woodhouse (2000b) identified non-viscous damping model using an exponentially decaying relaxation function. Phani and Woodhouse (2007) proposed that complex modes arising out of non-proportional dissipative matrix hold the key to successful modeling and identification of correct physical damping mechanisms in the vibrating systems but these identified complex modes are very sensitive to experimental errors and errors arising out from curve fitting algorithms. Some research efforts have also been made to update the damping matrices. Lin and Ewins (1994) proposed a response function method (RFM) to update mass and stiffness matrices using real part of FRF. Imregun et al. (1995) extended the response function method (RFM) to update proportional viscous and structural damping matrices by updating the coefficients of viscous and structural damping matrices. In this paper, it is referred as 'extended RFM'. Arora et al. (2009a) identified the structural damping matrix using complex frequency response functions (FRFs) of the structure. In this method, the updating parameters are assumed complex and the imaginary part of the complex updating parameter represents structural damping in the system. Arora et al. (2009b) proposed a viscous damping identification method in which viscous damping is identified explicitly. This procedure is a two steps procedure. In the first step, mass and stiffness matrices are updated and in the second step, viscous damping is identified using updated mass and stiffness matrices obtained in the previous step. Pradhan and Modak (2012) proposed FRF-based model updating method in which normal FRFs (NFRFs) is used for updating damping matrices along with mass and stiffness matrices.

In this paper, a new method of structural damping identification is proposed. The proposed method is direct method and requires estimation of full normal FRF matrix. The full normal FRFs are estimated from the full experimental complex FRF matrix. This method is applicable to simpler structures, where it is practical to get full FRF matrix. The proposed method also does not require initial damping estimates. The identified structural damping matrix $[D]$ is both general symmetric and positive definite. The effectiveness of the proposed structure damping