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Selective structural source identification

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ABSTRACT

In the field of acoustic source reconstruction, the inverse Patch Transfer Function (iPTF) has been recently proposed and has shown satisfactory results whatever the shape of the vibrating surface and whatever the acoustic environment. These two interesting features are due to the virtual acoustic volume concept underlying the iPTF methods.

The aim of the present article is to show how this concept of virtual subsystem can be used in structures to reconstruct the applied force distribution. Some virtual boundary conditions can be applied on a part of the structure, called *virtual testing structure*, to identify the force distribution applied in that zone regardless of the presence of other sources outside the zone under consideration. In the present article, the applicability of the method is only demonstrated on planar structures. However, the final example show how the method can be applied to a complex shape planar structure with point welded stiffeners even in the tested zone. In that case, if the *virtual testing structure* includes the stiffeners the identified force distribution only exhibits the positions of external applied forces. If the *virtual testing structure* does not include the stiffeners, the identified force distribution permits to localize the forces due to the coupling between the structure and the stiffeners through the welded points as well as the ones due to the external forces. This is why this approach is considered here as a selective structural source identification method.

It is demonstrated that this approach clearly falls in the same framework as the Force Analysis Technique, the Virtual Fields Method or the 2D spatial Fourier transform. Even if this approach has a lot in common with these latters, it has some interesting particularities like its low sensitivity to measurement noise.

1. Introduction

The identification or indirect measurement of forces acting on a structure by means of vibratory measurements has known important progresses during the last decades but remains a difficult question when the complexity of the structure increases. Indeed, contrary to acoustic source identification, each system is a particular case because of mechanical characteristics of the system (materials, boundary conditions, couplings, damping …). To overcome this issue two options are possible: the system can be known either through its equation of motion or through a preliminary learning step. The learning step often consists in preliminary measurements under controlled conditions (moving hammer for example) to acquire transfer functions characterizing the structure. These transfer functions can feed either a neural network [1], a genetic algorithms [2] or a time reversal method [3]. In a second step, in operational conditions, some signals are acquired to deduce if a force has been applied at a set of pre-selected positions (defined by the shock points). On the one hand, this category of methods does not need a model and can thus be applied on industrial structures. On the other hand, the forces can only be retrieved on few pre-selected points and

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this kind on methods are mainly dedicated to localization and ranking of forces.

If the exact positions of sources are unknown or if the aim is to deduce the force distribution applied on a structure, an updated model of the structure is mandatory. In that case, some methods have been developed based on a "strong" or a "weak" formulation. The Force Analysis Technique [4] uses the "strong" formulation of the equation of motion of a flat structure to deduce the applied force distribution estimating the derivatives by finite difference scheme. This method is thus local and does not depend on the shape or the boundary conditions of the flat structure. To identify the force applied at one point of the structure, one need measurements on a 13 points scheme centered on the point under study. This inverse method does not need any matrix inversion but it is still sensitive to measurement noise. A wavenumber filtering step is then necessary to retrieve the force distribution. A corrected finite difference scheme [5] has also been derived to intrinsically filter components associated to high wavenumbers. One interesting development of this method is the possibility of estimating the material properties of the structure in zones where no force is applied [7]. Also, the Force Analysis Technique was adapted to be applicable on more industrial cases using reduced Finite Element models [6].

Rather than estimating derivatives with finite different scheme, Zhang *et al.* [8] applied a 2D spatial Fourier transform on the equation of motion of a planar structure. The 2D Fourier transform on a displacement field on a regular rectangular mesh - whose size and step of discretization define the validity domain of the method - gives then access to the force distribution in the wavenumber domain. Finally, an inverse 2D Fourier transform of the latter allows estimating the force distribution in the spatial domain. This method also does not require matrix inversion and is independent of boundary conditions of the structure but is not local because of the 2D spatial Fourier transform.

These methods necessitate an updated model. Any difference between the model and the reality will generate residual equivalent forces. However, an updated model is not always available. In the case of an uncertain model, a Bayesian approach can be used [9,10].

In the case of a "weak" formulation, a *testing*, *virtual* or *weighting* 2D function that can be seen as "scanning window" is introduced. This function can have arbitrary form and has no need to respect any physical boundary condition. Several methods have been derived based on this principle. H. Xu *et al.* [11] chose a classic Gaussian function to detect structural damage on a structure, X. Xu *et al.* [15] defined the virtual displacement functions as trigonometric series to estimate the applied forces in the time domain. Chesné *et al.* [12] also used trigonometric series to identify the boundary forces applied on a plate. Berry *et al.* [13,14] developed the Virtual Fields Method on the use of Hermite16 interpolation functions. The "weak" formulation is often used to make the identification more robust against measurement noise.

Recently, a method called inverse Patch Transfer Functions (iPTF) method [16] has been derived based on the virtual acoustic volume concept. The aim of this method is to reconstruct the acoustic fields (velocity, pressure, intensity) on the surface of a vibrating source. A virtual acoustic volume is delimited around the source by the surface of the source and by the measurement surface. The iPTF method is also based on a "weak" formulation but the *testing* functions are defined as the mode shapes of the subdomain itself (i.e. the virtual acoustic volume) with particular boundary conditions. For the u-iPTF (iPTF with uniform Neumann boundary conditions) [17] a virtual acoustic volume with rigid walls is chosen whereas in m-iPTF (iPTF with mixed boundary conditions) [18] the considered virtual volume has rigid walls on the surface of the source and is open on the measurement surface. The u-iPTF necessitates the measurement of pressure and particle velocity on the virtual surface while m-iPTF only needs pressure measurements.

The present article deals with a "weak" formulation for reconstruction of force distribution using mode shapes of a part of the system itself as *testing* functions. The boundary conditions of this virtual *testing* structure can be arbitrary depending on the available measurements. As the mode shapes of the virtual *testing* structure is a basis of orthonormal functions, no regularization step is necessary and the approach has then low sensitivity to noise measurements. If the virtual *testing* structure is different from the corresponding part of the real *tested* structure, the differences appear as equivalent external forces on the reconstructed force distribution. This particularity can be used as a tool for updating Finite Element models.

The proposed theory is first presented and the applicability of the approach is demonstrated on a simply supported plate. Different virtual *testing* plates are used to reconstruct the force and the injected power distributions. Finally, an application on a more complex planar structure including stiffeners is shown. Two virtual *testing* structures (including and excluding stiffeners in the tested zone) are used to demonstrate that the proposed approach can be considered as a selective structural source identification method.

2. Theory

2.1. System under study

Let's consider the transverse displacement $W(M,\omega)$ at point M on a Love-Kirchhoff plate excited by any force distribution $F(M,\omega)$ as shown in Fig. 1. In the following, this plate will be denoted as the *tested* plate for which it is supposed that the exact shape and the boundary conditions are not known.

In harmonic regime, the equation of motion of the *tested* plate is given by

$$-m\omega^2 W(M,\omega) + D\Delta^2 W(M,\omega) = F(M,\omega), \quad (1)$$