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Prediction of the vibro-acoustic response of a structure-liner-fluid system based on a patch transfer function approach and direct experimental subsystem characterisation

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ABSTRACT

The vibro-acoustic response of a structure-liner-fluid system is predicted by application of a patch transfer function (PTF) coupling scheme. In contrast to existing numerical approaches, PTF matrices of structure and liner are determined by a direct experimental approach, avoiding the requirement of material parameters. Emphasis is placed on poroelastic lining materials. The method accounts for surface input and next-neighbour transfer terms and for cross and cross-transfer terms through the specimen. Shear stresses and transfer terms to further patches on the liner are neglected. A single test-rig characterisation procedure for layered poroelastic media is proposed. The specimen is considered as a single component – no separation of layers is performed. For this reason the characterisation procedure can serve as a complement to existing methods if separation of layers is not possible and as a tool for validation of more detailed material models. Problem specific boundary conditions for skeleton and fluid, which may cause non-reciprocal cross terms, are dealt with by the procedure. Methods of measurement for the assessment of PTF matrices are presented and their accuracy and limitations are discussed. An air gap correction method for surface impedance measurements is presented.

1. Introduction

Poroelastic lining materials are widely applied as dissipative treatments in vibro-acoustic systems. When a structure is radiating into a cavity, the insertion of poroelastic damping layers has three main effects: Structural loading and damping, decoupling the cavity from the structure (mass-spring systems) and adding absorption to the cavity.

In traditional numerical simulations [1], the influence on the structure is usually described by additional mass and damping. The damping imposed on the cavity by the poroelastic layer is captured by an impedance boundary condition in the simplest case. Required parameters may be estimated by material models, ranging from simple equivalent mechanical systems to phenomenological impedance models (e.g. [2]). Mechanical parameters of lining materials may be obtained in dynamic stiffness tests and impedances are measured in a standing wave tube or in situ on the material surface [3]. Depending on the type of lining material and the desired accuracy, more detailed models are required. A common approach is based on the Biot model for poroelasticity in a full FEM simulation [4] or in a reduced transfer matrix scheme [5]. Material parameters, such as porosity or flow resistivity can be obtained experimentally on material samples. Due to the variety of material properties (e.g. viscoelastic skeleton, anisotropy, etc.), modelling and characterisation of poroelastic material are an area of active research [6].

The patch transfer function (PTF) coupling scheme [7–9] has been introduced as a method to reduce the calculation time in coupled fluid/fluid and fluid/structure simulations. While having been developed for numerical applications, the relatively small number of discrete surface elements (patches) makes this approach also applicable to experimental characterisation of physical systems [10,11]. For structure-borne sound similar approaches have been introduced to couple subsystems by mobility matrices (e.g. [12]).

In this article the PTF methodology is applied to a physical structure/liner/fluid system with experimentally characterised structure and liner. The principles of the coupling method and the experimental realisation for the subsystem characterisation are presented. Particular emphasis is given to the liner characterisation method, which is non-destructive and can be performed on

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flat and isotropic samples. Non-local effects due to wave propagation in the lateral direction of the liner are accounted for by transfer terms. Propagation across the thickness of the material is described by cross terms. Mechanical separation of the layers, with the risk of modifying their characteristics, is not necessary.

The described direct characterisation methods are intended to capture the response of a subsystem as-is. For example if no reliable numerical models are available for a complex structure such as a car body, experimentally acquired patch mobilities may be used instead. A direct experimental liner characterisation may not only be of interest when no material models are available, but also for materials where a separation of layers is not possible or when parameters vary continuously across the sample thickness. However, results from a direct experimental characterisation do not allow for later adjustments in material parameters or geometry. For these reasons, the approach is considered as *complementary to* rather than as *a replacement for* micro-models based on material parameters. Since patch transfer matrices can also be computed from the latter, the proposed methods might be useful as an intermediate-step experimental verification of modelling results.

Characterisation results of isolated subsystems and the coupled system are presented in Section 4. An overview of the limitations of PTF coupling and characterisation methods can be found in Section 6. The range of validity is roughly set by the frequency where the wavelength in any of the coupled systems reaches the spatial aliasing limit. High dynamic range of sensors and highly accurate calibration and characterisation measurements are required to avoid random and systematic errors masking the results.

2. Theory

2.1. Patch transfer functions

This section introduces PTF coupling equations for a built-up system consisting of a structure, liner and fluid domain. The system is discretised by a patch grid as shown in Fig. 1. The arithmetic mean of complex field amplitudes is taken over each patch surface. Thereby, integral equations for infinitesimal elements and Green's functions are approximated by matrix equations for discrete patches. Detailed derivations of the patch transfer function method can be found in [7,9,13]. The present approach considers only out-of-plane velocities for the coupling procedure without explicitly including shear stresses when coupling to the liner. This is justified at least in the case of a thin plate-like structure, where in-plane and out-of-plane velocity are directly related and the directivity of the radiated wave is similar with and without liner [5]. If there is no direct contact between structure and liner (a thin layer of air in-between) it is also possible to neglect shear stresses [14].

In the following a slightly alternative matrix formulation is used to describe coupling between sub-systems. Structure and fluid are, as usual, characterised by respectively a mobility matrix $\mathbf{Y}$ and an impedance matrix $\mathbf{Z}$. Since patch-averaged pressures p_i and velocities v_i are the governing variables, an impedance or mobility term can be either interpreted as a patch-averaged acoustic surface impedance/mobility or a mechanical impedance Z_{mech}/S_p or mobility S_pY_{mech} normalised by a factor of the patch area S_p. The liner will be characterised by a hybrid matrix $\mathbf{H}$ instead of a conventional impedance matrix. A similar technique has been described by Atalla et al. [4] to integrate poroelastic materials into finite element models of structural and acoustic domains.

The interface between the liner and the structure (respectively the cavity) is referred to as face α (respectively face β, see Fig. 1). Positive velocities are directed upwards by convention, which leads to a change of signs in the mobility relation of the structure.

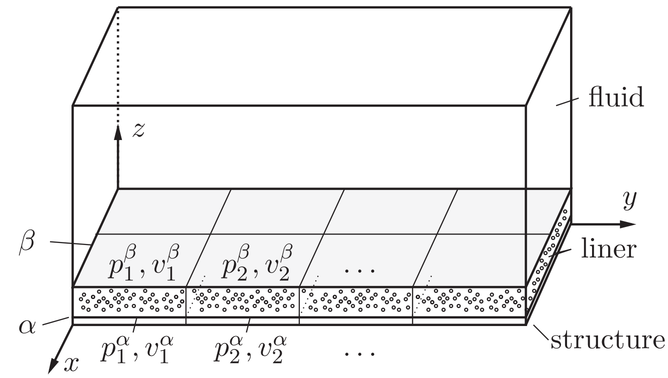

Fig. 1. Coupled system discretised into patches. The α and β superscripts indicate the structure/liner interface and the liner/fluid interface respectively.

The velocity response of the structure due to a pressure excitation on face α is given by

$$\mathbf{v}^\alpha = -\mathbf{Y}\mathbf{p}^\alpha. \tag{1}$$

The mobility $\mathbf{Y}$ is an intrinsic property of the structure, so relation (1) holds independently from the actual source of the pressure – whether it is due to an external excitation or due to the coupled response of another subsystem. If an excitation of $p_n^\alpha = 1$ at position n of an otherwise free ($p_{m\neq n}^\alpha = 0$) structure is applied, the resulting response velocities are the elements of the n-th row of $\mathbf{Y}$.

The fluid surface impedance on β relates pressures and velocities on the upper liner-fluid coupling surface,

$$\mathbf{p}^\beta = \mathbf{Z}\mathbf{v}^\beta. \tag{2}$$

This relation is again independent of the coupling and the n-th row of $\mathbf{Z}$ is equal to the hypothetically blocked ($v_{n\neq m}^\beta = 0$) pressures due to an excitation of $v_n^\beta = 1$ at position n.

A relationship between pressure and velocity on the two surfaces of the liner is given by the matrix equation

$$\begin{bmatrix}\mathbf{p}^\alpha\\ \mathbf{v}^\beta\end{bmatrix} = \mathbf{H}\begin{bmatrix}\mathbf{v}^\alpha\\ \mathbf{p}^\beta\end{bmatrix} = \begin{bmatrix}\mathbf{h}^{\alpha\alpha} & \mathbf{h}^{\alpha\beta}\\ \mathbf{h}^{\beta\alpha} & \mathbf{h}^{\beta\beta}\end{bmatrix}\begin{bmatrix}\mathbf{v}^\alpha\\ \mathbf{p}^\beta\end{bmatrix}. \tag{3}$$

$\mathbf{v}^\alpha$ describes a velocity (kinematic) excitation from the bottom side and $\mathbf{p}^\beta$ a pressure excitation from the top side.

For the one-dimensional case (one patch on each side), bottom and top quantities $\mathbf{p}^i$, $\mathbf{v}^i$ and sub-matrices $\mathbf{h}^{ij}$ are given by scalars p^i, v^i, h^{ij} that may be interpreted in the following way:

$$h^{\alpha\alpha} = \left.\frac{p^\alpha}{v^\alpha}\right|_{p^\beta=0} \tag{4}$$

is the impedance as seen from the bottom side while keeping the top side free (the inverse of the bottom mobility).

$$h^{\alpha\beta} = \left.\frac{p^\alpha}{p^\beta}\right|_{v^\alpha=0} \tag{5}$$

is the transmission ratio from a pressure excitation on the top to the blocked bottom.

$$h^{\beta\alpha} = \left.\frac{v^\beta}{v^\alpha}\right|_{p^\beta=0} \tag{6}$$

is the transmission ratio from a velocity excitation on the bottom to the free top.

$$h^{\beta\beta} = \left.\frac{v^\beta}{p^\beta}\right|_{v^\alpha=0} \tag{7}$$

is the top surface mobility (the inverse of the surface impedance) with a blocked bottom.