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Global optimisation methods for poroelastic material characterisation using a clamped sample in a Kundt tube setup

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ABSTRACT

The Biot theory is commonly used for the simulation of the vibro-acoustic behaviour of poroelastic materials. However, it relies on a number of material parameters. These can be hard to characterize and require dedicated measurement setups, yielding a time-consuming and costly characterisation. This paper presents a characterisation method which is able to identify all material parameters using only an impedance tube. The method relies on the assumption that the sample is clamped within the tube, that the shear wave is excited and that the acoustic field is no longer one-dimensional. This paper numerically shows the potential of the developed method. It therefore performs a sensitivity analysis of the quantification parameters, i.e. reflection coefficients and relative pressures, and a parameter estimation using global optimisation methods. A 3-step procedure is developed and validated. It is shown that even in the presence of numerically simulated noise this procedure leads to a robust parameter estimation.

1. Introduction

Due to increasingly restrictive legal regulations and increasing customer demands, the vibro-acoustic behaviour of products becomes a topic of high importance in for example the automotive sector and industrial machinery environments. The quest for lighter and hybrid cars to reduce the fuel consumption and the ecological footprint of the vehicles in general, inherently comes with deteriorated noise and vibration properties [1]. Therefore, these industries typically use poroelastic materials to keep noise limited to acceptable levels. Besides, the same quality has to be delivered in ever shorter time-to-market cycles. Therefore, the use of virtual prototyping tools has become an essential part of the design process.

Both aspects enlarge the need for a reliable simulation of the effect of poroelastic materials on the sound field. For vibro-acoustic simulations, the Biot theory [2], as adapted by Johnson et al. [3], Champoux and Allard [4] (JCA), is commonly used [5] and describes the dynamic behaviour of the poroelastic material by two coupled partial differential equations. The model applies a homogenised solid and a compressible fluid continuum description on a macroscopic level. It has been shown that this homogenisation is justified if the pore dimensions are much smaller than the wavelengths of the different waves propagating through the material. The Biot theory predicts the existence of three waves which propagate in both phases simultaneously: two longitudinal waves and one shear wave.

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Different numerical procedures such as Finite Element formulations e.g. [6–8], the Transfer Matrix Method [9], Trefftz approaches [10–12] and hybrid approaches [13] have been developed to predict the outcome of vibro-acoustic problem settings including poroelastic materials. Each method and formulation has its advantages and drawbacks, but the accuracy of the simulations using each of them logically relies on the accuracy of the material properties.

To describe the behaviour of the poroelastic material, the JCA model of Biot's theory uses a number of material dependent parameters, which can be related to properties of the frame material, properties of the fluid filling the voids, and the geometry of the pores, respectively. The standard properties of air are assumed to be known in this paper. The geometry of the pores determines the porosity ϕ, the tortuosity α_∞, the flow resistance σ, the viscous characteristic length Λ and the thermal characteristic length Λ'. Furthermore, the bulk density of the skeleton ρ_1, the complex Young's modulus of the frame in vacuum E and the complex shear modulus of the frame N depend on the solid constituent.

Currently, there are different approaches to obtain the above-mentioned parameters. For all parameters, dedicated tests and associated measurement setups, advantages and disadvantages have been discussed in the literature, see e.g. [5,14–17] and references therein. Parameters such as the porosity and airflow resistivity can be easily measured using standard techniques, while the others show to be more difficult to determine with sufficient accuracy. Besides, due to the use of different test setups, the characterisation of poroelastic materials is costly and time consuming. Other authors propose to determine multiple parameters at once, using optimisation strategies. The main example is the procedure described in [18], which applies an equivalent fluid model and uses Kundt tube measurements to determine the characteristic lengths and the tortuosity. This method has also been commercially implemented in FOAM-X, which in addition allows to extract ϕ and σ [19]. The use of transmission tube measurements to retrieve all parameters at once has been proposed in [20], however, large differences with respect to reference values are sometimes observed and it is indicated that the constrained edge of the sample may have an influence.

As has been shown in [21], round-robin tests to validate the reproducibility on measurements of the acoustic impedance and absorption of porous foams using a Kundt tube show a large spread on the results. It is indicated that specification of sample preparation and sample support should be included in the measurement procedure. This illustrates the sensitivity of measurement results to the test setup.

When considering impedance tube measurements, as has been shown in various studies, e.g. see [22–24], the mounting conditions can have an important impact on the results. When the sample is clamped into the tube, also the shear wave is excited and the sample has a stiffer behaviour. To account for these effects, analytical expressions are insufficient to accurately predict the dynamic behaviour in certain frequency ranges and numerical prediction techniques should be applied. When impedance tube measurements are applied for inverse material characterisation, analytical expressions are used, applying equivalent fluid models [18] or Biot models [20]. In the former case often needles are inserted in the samples to rigidify the porous material. This way, the effect of solid phase on the material sample is minimised and the behaviour of the poroelastic material better approximates the equivalent fluid behaviour. In the latter case it is presumed that sliding edge boundary conditions [25] are valid and that the sample is loosely fitting in the tube.

Recently an efficient numerical method has been developed which allows modelling an impedance test setup in which the sample is clamped into the tube [26]. The main goal of this paper is to exploit the fact that the sound field within the measurement tube is not one-dimensional when the sample is clamped into the tube. It will be shown that, given the assumption that fixed edge boundary conditions accurately represent the physical behaviour of the sample, it is possible to retrieve all poroelastic material parameters, performing one single measurement campaign and using a widely available and low cost impedance tube. Besides, it is validated whether the number and location of the microphones can be optimised to obtain a better convergence.

This paper is organised as follows. Section 2 describes the developed procedure and the numerical model used to support this procedure. Section 3 explains the assets of using a 2D model and describes the parameters used to quantify the sound field in the Kundt tube. This quantification is necessary to perform a parameter estimation using optimisation methods. Section 4 assesses the sensitivity of the different quantification parameters to the material parameters. This section also discusses the frequency dependency and the spatial dependency of the sensitivity. Section 5 assesses the use of global optimisation methods for parameter estimation. These optimisation methods use multiple starting points to obtain a better performance than local optimisation methods. A more robust parameter estimation procedure is presented. Section 6 describes the effect of noise on the optimisation performance. The paper concludes with a number of final remarks.

2. Problem description

This paper investigates whether a Kundt tube measurement setup can be used (with minor adaptations) in combination with efficient numerical simulations using the Wave Based Method (WBM) to estimate all parameters of a poroelastic material, associated with both the fluid and the solid phase. To this extent, this section first briefly explains the Biot theory of poroelasticity. Thereafter, a short description of the measurement setup and the WBM model are given.

2.1. Poroelastic materials

The Biot theory [2,5] is most commonly applied to model the mutually coupled dynamic behaviour of the skeleton and the interpenetrating fluid inside a poroelastic material. It applies a homogenisation of the material into a separate solid and