A comparison and review of theories of the acoustics of porous materials

Michael R. F. Kidner and Colin H. Hansen[‡]
Acoustics Vibration and Control Group, School of Mechanical Engineering, The University Of Adelaide, Adelaide 5005

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This article reviews the research on acoustic waves in porous media. Particular emphasis is placed on the relationship between the full Biot–Allard model and the simpler approximations presented by Zwikker and Kosten, Morse and Ingard, and others.[1–3] A comparison of several models used to predict the absorption characteristics of porous materials is presented.

‡Fellow of the International Institute of Acoustics and Vibration (IIAV)

1. INTRODUCTION

Porous materials are commonly used in noise control applications because they are very easy to install and provide excellent absorption at mid to high frequencies. Although these materials are widely used, the theoretical modelling is surprisingly complex, so empirical approximations are often used.[4] These approximations often prove to be valid for most practical applications; however, researchers have shown that a complete theory can shed light on unexpected behaviour. A complete theoretical description of waves in porous materials was obtained by Biot in 1956.[5,6] The theory described the motion of the fluid in the pores and the motion of the solid pore walls, or frame. Since that time, a vast quantity of work has been done to apply this theory to many diverse fields including acoustics, geo-mechanics, and bio-dynamics as discussed below.

Sound absorbing materials Porous materials have been used for sound and vibration absorption because of their efficacy, cost effectiveness, and simplicity to install. The focus of this paper is the modelling of the process of sound propagation within these materials. The discussion will follow the theoretical models derived using rigid frame assumptions, as illustrated in Fig. 1, to a model that includes an elastic frame, as shown in Fig. 5.

Geomechanics & Ocean Acoustics Porous mechanics is applied most widely in the field of geo-mechanics.[7] The prediction of soil motion during earthquakes is a particularly important topic. The propagation of seismic waves through porous rocks can yield valuable information for mineral and fossil fuel explorations. Oceanography has also benefited from the more complete model of the ocean floor that the porous media models provide.[8] Biot's description of porous materials accurately predicts how acoustic energy travels through ocean sediments and rocks.[5,6] Descriptions of granular materials such as those by Berryman and Morse are applicable to the propagation of acoustic energy through ocean sediments and rocks.[9,10]

Biological Systems Biological systems such as lungs and bones can also be modelled as porous materials. The prediction of the acoustic response in these materials is increasingly relevant to ultrasonic imaging as greater resolution becomes necessary. Ultrasonic propagation in bovine bones has been predicted[11,12] using Biot's equations.[5] Reflection and transmission of ultrasound pulses through bone is the focus of many bio-mechanics research papers on waves in porous media.

1.1. Paper Overview

The dynamics of porous materials are complex, not only because porous materials come in different forms, but also because of the micro and macroscopic scales required to fully describe them. This results in an unsatisfying mix of crude approximations and obtuse detail, often within the same model! Attenborough gave a thorough review of the detailed modelling of porous materials in which he consolidated many of the approaches and described their assumptions in great detail.[13]

This paper will attempt to summarise the most common approaches to modelling porous materials with respect to acoustic waves. The paper is laid out as follows: The simple Delany–Bazley approximation is reviewed, and this is probably the model with which most readers are familiar.[4] From this point, the discussion focuses on the microscopic scale and reviews descriptions of fluid flow through pores, as the majority of research from 1890 to 1950 concentrated on this mechanism. The Biot model, which is currently accepted as the most complete description of porous dynamics, is then discussed.[5,6] In the penultimate section, the Biot equations are reviewed with reference to their application to numerical methods for solving acoustics problems, such as the prediction of transmission loss through double panels with porous liners.

At each stage, the sound speed predicted by the various models is shown. In the penultimate section, the difference in the sound absorption predicted by each of the methods is discussed.

2. THE DELANY–BAZLEY APPROXIMATION

Delany and Bazley developed a simple empirical model of the acoustic impedance of a porous material based on its flow resistivity, R_1.[4] Flow resistivity is defined as the pressure required to generate a unit flow through the material per unit thickness. A material with a low porosity, ϕ and complicated micro structure is likely to have a higher flow resistivity than