The Numerical Simulation and Measurement of a Schroeder Diffuser

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Abstract

Number theoretic diffusers have been widely used in architectural acoustics for the design of concert halls and listening rooms in order to improve acoustic diffusion. In-field measurements show that significant sound absorption is introduced into room by the diffusers, especially in the low frequency range. This paper studies the absorptive performance of periodic Schroeder diffusers using both experimental and computational approaches. The experiment was carried out in a reverberation chamber using different arrangements of diffusers. The motion of the fluid adjacent to the diffuser was simulated using a finite difference method (FDM) for the full compressible Navier-Stokes equations.

Introduction

Number theoretic diffusers have been widely used in architectural acoustic applications since Schroeder introduced them in the 1970s. They were designed to diffuse sound, but substantial absorption, especially in the low frequency range, was observed and measured by Fujiwara and Miyajima[1]. Two methods have been used to explain and predict the absorption of the diffuser. One is based on a constant sound pressure in the diffuser plane and the same average surface admittance by Kuttruff[2]. In Wu's paper[3], a Fourier wave decomposition model was discussed and applied to a single diffuser. Previous theories were based on a 1-dimensional Schroeder diffuser unit, assuming the walls between wells were parallel and with normal incident acoustic waves, which would not happen in practical applications. In practical situations, diffusers are used in groups to form a large diffusion surface. The structural anisotropy of the diffuser groups and the coupling between wells makes the sound absorption different to that in a single unit. It is important for room acoustics to study the acoustic diffusion and absorption in the near and far field with random incidence acoustic waves. In order to study the physical mechanisms of energy loss, an approach based on a Computational Fluid Dynamics (CFD) method for low Mach number flow was taken.

In the first part of this paper, absorption coefficients for a quadratic residue diffuser (QRD), one kind of Schroeder diffuser, is measured in a reverberation chamber. The performance of diffusers with different arrangements of units are studied and compared. In the second part, the method and preliminary results for a semi-implicit method for solving the Navier-Stokes equations at low Mach number flow is briefly discussed.

Test sample and Experimental results

A numeric diffuser consists of wells with different depths but similar widths. The quadratic residue sequence for one period of a one-dimensional QRD is defined as:

$$S(n) = (n^2)mod(N), n = 0, 1, ..., N-1 \qquad (1)$$

where N is the prime number. The wells' depths l_n are given by:

$$l_n = \frac{cS(n)}{N(2f_r)}, n = 0, 1, \ldots, N-1. \qquad (2)$$

where f_r is the design frequency and also the lower limit of the effective frequency range of the diffuser, and c is the sound speed.

Parameters of the QRD samples measured are: size approximately 66 cm $\times$ 66 cm, prime number $N = 11$, design frequency $f_r \approx 390Hz$, maximum depth of wells 36 cm, well width 5 cm, and separation wall thickness 0.9 cm. The depth sequence is (in cm):

0 4 16 36 20 12 12 20 36 16 4

The diffuser samples are rigid and the hard boards blocking off the wells did not vibrate in the measurements.

In the experiment, the measurement of sound absorption in a reverberation room (ISO/FDIS 354:2003) was applied. Reverberation times were measured of the empty chamber and the chamber including the diffusers. 24 diffusers in a group were measured. 1D and 2D arrangements of diffuser units were used in the experiments as shown in fig 1.

Abbildung 1: Two different diffusers arrangements. Left: 1-Dimensional; Right: 2-Dimensional.

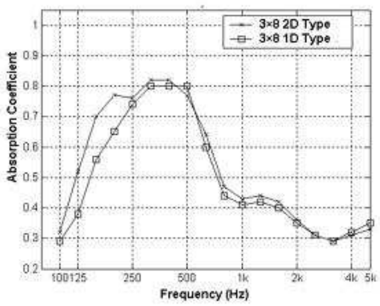

Abbildung 2: The effective sound absorption coefficient of two diffuser arrays in a reverberation chamber.

Significant sound absorption was observed in fig 2, especially around the design frequency f_r in the low frequency range. The different diffuser arrangements had different surface impedance distributions but this did not lead to significant differences in the middle and high frequency range. In the frequency range below the design frequency f_r, the 2D arrangement has a higher absorption coefficient than the 1D arrangement.

Numerical Simulation

The incident acoustic waves are not only reflected and diffused but also drive the fluid motion adjacent to the diffuser. This energy transferred from the sound to the local flow is subsequently dissipated by the effects of viscosity and heat transfer. In order to simulate both the nonlinear fluid motion and the acoustic waves accurately, the full compressible Navier-Stokes equations need to be solved. This can be a challenge for the computational method because the acoustic pressure perturbation can be several orders of magnitude smaller than the thermodynamic pressure and the propagation speed several orders of magnitude larger than the fluid motion absorbing the acoustic energy. A semi-implicit approach for solving the Navier-Stokes equations at low Mach numbers was adopted based on the previous work of [5]. This uses a second order centered finite differencing scheme in which the velocity components are staggered in both space and time. The semi-implicit approach allows the time step to be larger than the CFL limit which would be a severe restriction for a traditional high Mach number explicit compressible CFD method.

Fig 3 shows the pressure and velocity fields for the fluid adjacent to the diffuser at two different times. A strong fluid motion between adjacent wells is caused by unequal pressures at the outlet of the wells with different depths and introduces a motion that will mainly lead to a local energy loss rather than a radiation of energy to the far field. The preliminary computational study revealed several numerical issues that require further attention such as the balance between numerical dissipation and the generation of spurious unresolved high frequency acoustic waves and the difficulties in implementing a suitable boundary condition for the left hand side in the figure which imposes the incoming acoustic waves while allowing outgoing acoustic waves to leave without being significantly reflected.

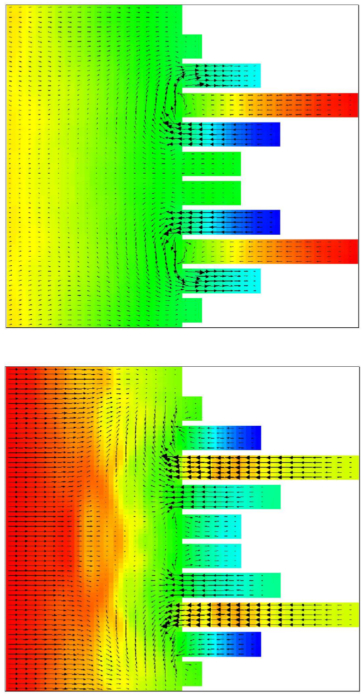

Abbildung 3: Pressure (color) and velocity (black arrow) fields at two times due to an incident acoustic plane wave

Conclusion

The experiments have shown that the Schroeder diffuser has significant sound absorption in the low frequency range and that different arrangements have little effect on the absorption performance. From the preliminary numerical simulations the coupling between the wells has been shown but several numerical issues require further attention before the method is used in a broad computational study.

Literatur

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