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Transmission conditions for simulating acoustic propagation in complex flows

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Abstract

Firstly, a generic construction of transmission conditions for aeroacoustics from a unidirectional numerical factorization of the propagation operator is presented. Then, from these conditions, an iterative domain decomposition method based on fast local One-Way solvers is developed. Finally, the relevance of this new method is highlighted in the context of a partially lined duct.

Keywords: Transmission conditions, domain decomposition method, One-Way equations, aeroacoustics, acoustic liners.

1 Introduction

Transmission conditions are of crucial importance for sorting the information entering and leaving a computational domain, but also for constructing efficient numerical schemes such as those based on Domain Decomposition Methods (DDM) or One-Way (OW) equations. Deriving these conditions in the context of aeroacoustics is a difficult task due to the non-homogeneous nature of the propagation medium, and remains an active area of research today.

A first important work in this context is a purely numerical OW method applied to linear hyperbolic equations proposed by Towne & Colonius for slowly varying flows [1]. A second work is a new factorization of the propagation operator for the linearized Euler equations developed in [2], which allows accessing a refraction/reflection operator and to derive several OW solvers.

Based on previous work, we propose three extensions:

1. A numerical approach to construct transmission conditions.
2. A new scheme based on a DDM and local OW solvers.
3. An application of these tools to a partially lined duct in presence of an unstable surface mode for the linearized Euler and Navier-Stokes equations.

2 Transmission conditions for aeroacoustics problems

We present the main steps involved in the derivation of transmission conditions for wave propagation in complex regular flows. We assume that the direction of propagation, x , is imposed by the mean flow, and we are therefore interested in the derivation of these conditions only in this direction. In this framework, the hyperbolic part of the aeroacoustic equations, such as the linearized Navier-Stokes equations, can be rewritten as follows:

$$\frac{d\phi}{dx} = \mathbf{M}(x)\phi, \quad (1)$$

after a first discretization in the transverse direction (with appropriate boundary conditions), where \mathbf{M} is the semi-discrete propagation operator. In [2], a numerical factorization of \mathbf{M} is proposed and leads to an accurate identification of left and right invariant spaces (i.e., left and right modes, respectively). As a result, the factorization takes the form of:

$$\mathbf{M} \approx \tilde{\mathbf{M}} = \tilde{\mathbf{U}}^{-1} \tilde{\mathbf{D}} \tilde{\mathbf{U}}, \quad (2)$$

where $\tilde{\mathbf{D}}$ is a block diagonal matrix whose two blocks contain the spectral information of the left- or right-going modes and the N_+ first rows (respectively N_- last rows) of $\tilde{\mathbf{U}}$ define a projector on the N_+ -dimensional right invariant space (respectively N_- -dimensional left invariant space).

Consequently, $\tilde{\mathbf{U}}$ produces an incoming transmission operator γ_{in} and an outgoing γ_{out} transmission operator which are written as follows:

$$\begin{cases} \gamma^{in} \phi = \tilde{\mathbf{U}}_{N_++1, \dots, N_++N_-, * } \phi, \\ \gamma^{out} \phi = \tilde{\mathbf{U}}_{1, \dots, N_+, * } \phi. \end{cases} \quad (3)$$

3 A domain decomposition method

Using the transmission conditions (3), we can construct DDM for aeroacoustics in smooth heterogeneous mean flows with a preferred direction (here x). To do so, we introduce a computational domain $\Omega \subset \mathbb{R}^d$ ($d = 2, 3$) defined by

Mean flow type	x -independent	Slowly varying in x	General case
2D/3D numerical factorization complexity	$N_y^2/(N_y N_z)^3$	$N_{\text{sample}} N_y^3 / N_{\text{sample}} (N_y N_z)^3$	$N_x N_y^3 / N_x (N_y N_z)^3$
OW method (see [2])	Standard	Standard or True Amplitude	Bremmer series

Table 1: Overview of OW methods: (N_x, N_y, N_z) is the discretization grid and $N_{\text{sample}} \ll N_x$.

$\Omega = \cup_{x \in [0, L_x]} (\{x\} \times \Omega_{T,x})$, where $\Omega_{T,x} \subset \mathbb{R}^{d-1}$ represents the transverse part of Ω at the point $x \in [0, L_x]$. The DDM consists of three elements:

- A non-overlapping partitioning of Ω with respect to the direction x : $\Omega = \cup_{i=1}^N \Omega_i$ where $\Omega_i := \cup_{x \in [x_{i-1}, x_i]} (\{x\} \times \Omega_{T,x})$ with $[0, L_x] = \cup_{i=1}^N [x_{i-1}, x_i]$.
- A fast local solver based on OW equations derived from (2) (see Tab. 1 for some characteristics): the resolution of the aeroacoustic equations in each subdomain Ω_i is performed by alternating left and right OW solvers.
- A global iterative resolution process with information transmitted across subdomain interfaces using (3).

4 Application to partially lined ducts

We consider a 2D rectangular duct of height h with an acoustic liner on the down wall (see Fig. 1) and a parallel mean flow characterized by the axial velocity:

$$\bar{u}(y) = Ma(n_y + 1)/n_y (1 - |1 - 2y/h|^{n_y})$$

where a is the speed of sound, M the Mach number and n_y is chosen to ensure an accurate representation of the experimental mean flow.

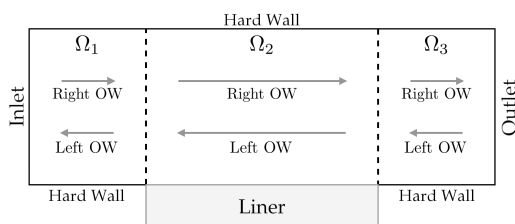


Figure 1: DDM configuration.

The DDM is implemented by considering three subdomains separated by interfaces at the leading and trailing edges of the acoustic liner (see Fig. 1). The two OW solvers used here (OWE for Euler and OWNS for Navier-Stokes) are valid in each subdomain, and the refraction and reflection phenomena induced by this partially coated configuration are taken into account by the transmission conditions which ensure the physical continuity at convergence. The

simulation parameters are $f = 1000$ Hz, $n_y = 5$ for the OWE and $n_y = 7.5$ for the OWNS (these values are imposed by the method's ability to deal with the thin boundary layer thickness), a Reynolds number of 4.8×10^5 and a discretization grid $(N_x, N_y) = (2000, 173)$. In Fig. 2, the efficiency of the numerical method for Sound Pressure Level (SPL) is shown based on a classical benchmark and by comparison with experimental data [3]. Contrary to the OWE, the OWNS is able to capture well the unstable surface mode at this frequency. This could be explained by a more accurate mean flow profile and the consideration of viscosity. The DDMs converge in 4 iterations for pressure continuity errors at the interfaces of 0.02% for the OWE and 0.1% for the OWNS. The CPU time for the OWE/OWNS is 1.4 s/3.2 s for the factorization and 30 s/51 s for the x -marching algorithm based on a second-order upwind discontinuous Galerkin scheme.

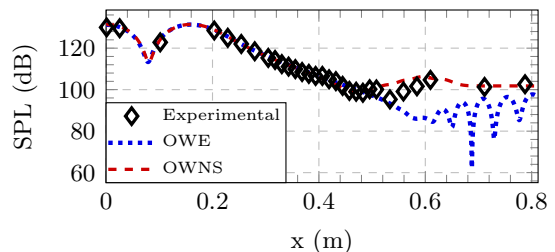


Figure 2: SPL along the upper wall.

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