Introducing Lined-wall Boundary Conditions in the DLR Time-domain CAA Solver PIANO

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Introduction

Understanding the physical mechanisms featuring in the aeroacoustics of lined surfaces is a key issue for the optimal design of passive sound absorbers (liners) in aircraft engines. The liners play an important role to reduce the noise emitted by modern aircraft engines. Engine and engine-nacelle manufacturers base their designs on gathered past experience and, more recently, on computational-aeroacoustics (CAA) solutions, including impedance-type boundary conditions to simulate the presence of liners in various regions of the engine-duct walls. The DLR CAA software PIANO can be used to simulate the evolution of an inviscid small-perturbation aerodynamic field at the presence of a prescribed background flow. The present work deals with the introduction of an impedance slip-wall boundary condition in PIANO, allowing for the simulation of acoustic propagation at the presence of locally-reacting acoustic liners. An extended-Helmholtz-resonator (EHR) model, as introduced in Ref. [1], is used in the present implementation. The implementation follows the approach indicated by Richter in Ref. [2]. In the present paper a brief summary of the implemented theory and the first results obtained by means of PIANO, with impedance wall, are presented. The presented results simulate a problem of plane-wave propagation through the DLR-Berlin liner-testing rig, described in Ref. [3], with a liner sample placed along a limited axial region of the duct bottom wall. In order to perform a qualitative-behaviour validation of the EHR impedance model, two different approaches are followed to model the effect of the liner sample.

1. An EHR uniform impedance slip wall is used as computational-domain boundary condition at the interface with the liner.
2. A geometrically detailed mesh is designed, where the liner is modelled as an array of rectangular hard-wall cavities.

The CAA software PIANO

The DLR software PIANO, described in Ref. [4], implements a solver for the linearised and weakly-non-linear Euler equations. PIANO can also be used as a solver for a set of acoustic-perturbation equations, Ref. [4]. In the present work, PIANO is used only as a solver for the linearised Euler equations (LEE). In PIANO the LEE are solved in the time domain by using a finite-difference scheme. The time-marching algorithm uses a high-order Runge–Kutta method; a 4-stage scheme and a low-dissipation-low-dispersion scheme, as introduced in Ref. [6], are both available in PIANO. A high-order DRP scheme is used for the spatial discretisation, as introduced by Tam & Webb in Ref. [5]. The scheme features a 7-point symmetric stencil, with coefficients that discretise spatial derivatives with order-4 accuracy and minimise numerical dispersion.

The EHR impedance slip wall

In the present work a new boundary condition on the LEE field variables is implemented, to realise a finite-impedance slip wall in PIANO. The implemented boundary condition adopts an EHR model, Ref. [1], to provide a time-domain description of a uniform-impedance locally reacting slip wall. As described by Richter in Ref. [2], for an EHR model in the time domain the perturbation acceleration normal to the impedance surface $\dot{u}'_n$ can be represented as a function of the acoustic pressure p' and the acoustic-velocity component u'_n (normal to impedance surface). Assuming zero flow tangentially to the impedance surface, the impedance-wall relation is expressed as follows:

$$\begin{aligned}\dot{u}'_n(t) = & \frac{1}{m_w}\left[p'(t) - (R_w + \beta_w)\, u'_n(t)\right] \\ & -\frac{e^{-\varepsilon_w}}{m_w}\left[p'(t - T_w) - (R_w - \beta_w)\, u'_n(t - T_w)\right] \\ & + e^{-\varepsilon_w}\; \dot{u}'_n(t - T_w) \qquad (1)\end{aligned}$$

Here the parameters m_w, R_w, β_w, ε_w and T_w respectively indicate the face reactance and resistance, the cavity reactance, resistance and time delay associated with the EHR model. Note that the assignment of the normal perturbation acceleration at a given spatial location on the impedance surface, as in expression (1), requires the knowledge of the field variables at the current time t and at a past time $t - T_w$. For the impedance wall, the values of p', u'_n and $\dot{u}'_n$ need to be stored for a number of time steps, covering the time history down to the T_w time delay. The present implementation projects the normal acceleration assignment (1) on the residuals of the Runge–Kutta scheme; the pressure perturbation at the wall is corrected, to guarantee the momentum balance within the DRP scheme; the density perturbation at the wall is set as $\rho' = p'/c_0^2$.

Numerical results

We propose simulations of the acoustic field over the liner-sample surface in the DLR-Berlin liner test rig.[1]

[1]The DLR-Berlin liner test rig is a square-section (side 80 mm) rigid-wall duct with an orifice, where a liner sample can be fit. The duct has a straight axis and terminates with low-reflection horn-shaped endings. Acoustic excitation is provided by means of loudspeakers mounted on the duct top wall; harmonic excitation is given at a frequency below the first high-order-mode cut-on

The simulations are proposed in 2D, without a background flow. The computational domain reproduces an axial section of the liner test rig, including an idealised liner sample; it is shown in Fig. 1 for the geometrically detailed hard-wall approach. A prescribed plane-wave

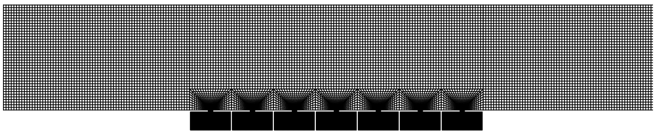

Figure 1: Part of the computational domain for the geometrically detailed hard-wall test case. The cell dimension inside the cavities is a tenth of the one in the duct section. The complex geometry and the requirements of the spatial-discretisation approach imply an acoustically over-resolved mesh (only plane-wave propagating patterns are introduced as acoustic excitation) and a very small time step.

time-harmonic acoustic field is injected in the hard-wall region of the duct. It is then let propagate over the liner sample and further, through the hard-wall duct, towards the low-reflection termination. Absorbing boundary conditions are applied at the duct extremities, in order to simulate the anechoic terminations of the rig. Acoustic-field solutions are reported in Fig. 2, as contour plots of the acoustic-pressure field. They are shown for both the geometrically detailed approach and for the newly implemented EHR boundary condition.[2] The solutions of Fig. 2 are very different in terms of

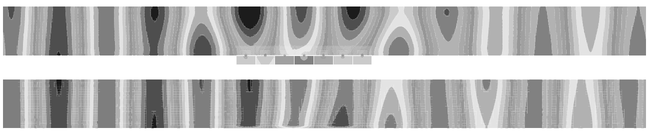

Figure 2: Piano simulation of the acoustic pressure field in the duct region over the liner sample, at a given time sample. The geometrically-detailed-model solution is reported on the top. The bottom solution is obtained by applying the implemented EHR boundary condition at the bottom wall of the duct, limited to the liner-sample axial region.

computational cost: the EHR resonator solution can be determined with 1% CPU time and reduced use of memory, compared to the detailed-geometry model. For both the EHR and the geometrically detailed models, the acoustic-pressure pattern over the liner surface sensibly differs from the plane-wave pattern that is introduced as prescribed acoustic perturbation and is still found in the solution at a distance from the liner sample. This fact is compatible with energy scattering from the initial plane-wave pressure pattern to non-propagating higher-order acoustic modes, whose pressure patterns are visible in the vicinity of the liner sample. Both solutions in Fig. 2 have been obtained by using a spatial filer, removing unstable parasite waves from the LEE solution; an analysis of the corresponding numerical dissipation is thus required, in order to quantitatively evaluate the transmission loss due to the presence of the liner sample. Nevertheless an insertion loss between the incident and the transmitted acoustic fields, due to the presence of the liner model, is present in both solutions and comparable in magnitude. For the geometrically-detailed model, given the absence of viscous dissipation, the insertion loss can be principally attributed to the effect of modal scattering to non-propagating acoustic modes and reflection.

frequency. This allows for assuming a plane-wave acoustic-pressure pattern in the hard-wall-section region of the duct. The liner-sample orifice is rectangular and it opens at the bottom wall; it is characterised by an axial length of 210 mm and a tranverse length of 80 mm. A background flow can be introduced by connecting the duct to an air-supply unit. This allows for studying the response of liner samples at the presence of a grazing flow. For a more detailed description of the test rig the reader is addressed to Ref. [3].

[2] The EHR model parameters are set as: m_w=0.1, R_w=1, β_w=ε_w=0 and T_w=0.0274. Note that the non dimensional time-delay T_w has been chosen based on the cavity depth, in the geometrically detailed model, and the non-dimensional speed of sound.

Conclusion

An extended Helmholtz resonator impedance has been introduced in the CAA software PIANO, in order to simulate the presence of lined surfaces in acoustic-propagation problems. The model has been used to determine a solution for zero-flow plane-wave propagation through a hard-wall duct, including a limited lined-wall surface. The obtained solution contains similar physical effects as in an analogous PIANO solution. The analogous solution was obtained through an idealised geometrically-detailed model, representing the liner as an array of cavities connected to the computational domain.

Acknowledgements

The present work has been made as part of the project “Buergernahes Flugzeug am Campus Forschungsflughafen Braunschweig.” The funding, provided by the Bundesland Niedersachsen and by the DLR, is gratefully acknowledged.

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