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Towards an effective non-reflective boundary condition for computational aeroacoustics

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ABSTRACT

A generic, non-reflective zonal transverse characteristic boundary condition is described for computational aeroacoustics, which shows superior performance to existing non-reflective boundary conditions for two-dimensional linearized Euler simulations. The new condition is based on a characteristic non-reflective method, and also contains optimised use of transverse characteristic terms and a zonal forcing region. The performance of the new method and several existing non-reflective acoustic boundary conditions is quantitatively compared using a plane wave test case. The performance of buffer zone, perfectly matched layer, far-field, and characteristic non-reflective methods is compared, following an optimisation of the tuneable parameters in each method to give best performance. The study uses a high-order linearised Euler equation solver to assess non-reflective boundary conditions with a variety of cases. The performance is compared for downstream travelling acoustic waves with varying frequency and incident angle, and at various Mach numbers. The current study includes a more comprehensive evaluation than previous studies which used constant values of tuneable parameters or qualitative assessment methods. The new zonal transverse characteristic boundary condition is shown to give improved performance in comparison to the other tested outflow boundary conditions for two-dimensional linearized Euler simulations, and is also shown to give good performance when used as an inflow condition.

1. Introduction

Computational aeroacoustic (CAA) simulations require effective non-reflecting boundary conditions (NRBCs) at the edges of a domain. A computational domain is usually truncated (i.e. it does not stretch to infinity) in order to reduce the computational cost. This truncation, combined with the use of numerical discretisation schemes that are optimised for minimal dispersion and dissipation errors, can cause simulations to be sensitive to spurious reflections from outgoing acoustic, vortical, or entropy waves impacting the domain boundaries.

Different methods have been used to obtain NRBCs. These methods have been developed for various governing equations, including the Navier-Stokes, Euler, and linearised Euler equations (LEEs). This paper applies NRBCs to simulations that solve the LEEs. Despite a variety of developed methods in literature, no single method exists to remove all reflections in all circumstances. Factors such as the frequency, meanflow non-uniformity, wave angle, and Mach number, can affect the

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performance [1]. This work describes a method that has superior non-reflective behaviour, and provides a thorough quantitative comparison of the performance of different NRBCs. More effective NRBCs are desirable because they reduce the sensitivity of simulation accuracy to the shape and size of the computational domain, thus allowing for reduced domain sizes in order to reduce the computational expense. The following are addressed in this work:

- A zonal transverse characteristic boundary condition (CBC) method, termed the zonal TCBC method, is proposed to improve non-reflective performance for acoustic waves when performing linearized Euler simulations. This method was first proposed in a previous publication by the authors [2]. However, a more complete description and evaluation of the method is given here.
- The plane wave test case of Richards et al. [1] is used in two-dimensional simulations to provide simple and fast quantitative comparison of the performance of NRBCs based on buffer zones, perfectly matched layers, characteristics, and far-field approximations.
- The zonal TCBC method is also evaluated as a non-reflective inflow condition, and its performance is compared with an implicit buffer zone method.

2. Methods to prevent reflections at domain boundaries

One method to prevent reflections from the domain boundaries is to modify the edges of the simulation domain. Alterations, such as ensuring the domain edge is normal to the incident wave or applying grid stretching, can significantly reduce reflections. However, in some situations, when studying duct acoustics or turbo-machinery for example, the geometric configuration may not allow for these changes to the domain boundaries. Therefore, non-reflective conditions must be applied at the domain edges. Three major categories of NRBCs are those based on asymptotic far-field solutions, characteristic methods, and on buffer zone techniques. Comprehensive reviews of the different methods exist, by Colonius [3], and Tam [4], for example. Therefore, only a summary is given here.

A widely used NRBC is based on characteristic methods. This method was developed by authors such as Thompson [5,6], Poinsot and Lele [7], and Giles [8]. This method performs a one-dimensional characteristic analysis at the domain boundaries. The value of characteristic waves entering the domain is set as zero in order to prevent reflections. However, this method is one-dimensional and is not effective for waves which approach the boundary at oblique angles. Some authors, such as Yoo and Im [9], have extended the method to consider two-dimensional problems with some success. This was done by including the transverse characteristic wave terms with a relaxation treatment. However, Yoo and Im's method [9] was based on a low Mach number analysis. Liu and Vasilyev [10] developed a non-linear multidimensional characteristic method that showed improvements in comparison to previous one-dimensional characteristic methods. CBC methods are usually applied at the edge of the computational domain. However, in some previous CAA studies [11,12], CBCs have been combined with buffer zone regions to improve the performance for oblique waves. Sandberg and Sandham [13] proposed a zonal CBC method where the amplitude of the incoming characteristic wave is gradually ramped to zero at the outflow. This was shown to significantly reduce reflections caused by outgoing vortical structures, since any reflected waves are contained within the zonal CBC region and do not propagate back into the domain.

Non-reflecting conditions based on asymptotic far-field solutions were proposed by Bayliss and Turkel [14]. Tam and Webb [15] also developed a radiation condition, which assumes that acoustic waves radiate spherically from a point source in a uniform meanflow. This assumption permits the solution of alternative governing equations in a region at the edge of the domain. Tam and Dong [16] extended this technique to consider weakly non-uniform meanflows. However, limitations still exist for complex flow regimes.

Non-reflective conditions based on buffer zone techniques attempt to damp the flow-field to a prescribed value at the domain edges. This prevents waves from reaching the edges of the domain and thus prevents them from causing reflections. The domain is extended to include a buffer region in which the damping occurs. This can be achieved via numerical damping [1,12,17], grid stretching [18], or by accelerating the flow to supersonic speeds at the boundary [19]. The buffer zone method can provide good performance and is easy to implement, but the flow-field within the buffer zone itself is non-physical, and the extension of the domain can increase computational expense. The amount of damping is usually ramped from zero in the domain to a prescribed amount at the edge of the simulation. Therefore, as with some other non-reflective boundary methods, buffer zone methods contain parameters which must be empirically tuned to optimise their performance. These parameters typically control the shape and strength of the damping ramp function.

A variation of the buffer zone method is known as the perfectly matched layer (PML). A different formulation of the damping layer is solved in the buffer region, such that any reflections due to the damping process are avoided. In other buffer zone methods, reflections can occur as a result of the damping process if it is too abrupt. The PML method was first formulated by Berenger [20] and first used for CAA simulations by Hu [21,22]. Tests have found good results when using the PML method to solve the LEEs, although it is difficult to apply to simulations using the Navier-Stokes equations. Additionally, some PML formulations, such as Ref. [23] for example, can suffer from long-term instabilities and can be ill-posed in some circumstances. More recent formulations have overcome these difficulties [22].

Some previous studies have assessed the relative performance of different NRBCs. Hixon et al. [24] compared the performance of Thompson's [5] and Giles' [8] CBC methods with the far-field condition of Tam and Webb [15] when simulating

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