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A low-reflection, fast-convergence NSCBC methodology for transient and unsteady compressible flows

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A crucial factor in ensuring the stability of compressible flow simulations is the appropriate treatment of boundary conditions to handle complex transient flows. The Navier-Stokes Characteristic Boundary Condition (NSCBC) method introduced by Poinsot and Lele [1], combined with a Linear Relaxation (LR) approach toward user-defined target values, remains a widely adopted strategy to address this challenge. The LR method enforces ingoing waves (i.e. waves entering the domain) based on a proportional correction derived from the measured error in the Quantity of Interest (QoI) relative to its target value. This error is simply the difference between the measured and target values [1]. Despite its robustness, this approach presents a trade-off between two competing objectives: reducing acoustic reflections and maintaining the desired mean target values. The dynamic response of the boundary condition is strongly influenced by this trade-off, yet its implications have received limited attention in the literature, despite the notable increase in computational costs it entails. While strategies proposed by Daviller et al. [2] and Polifke et al. [3] have sought to improve acoustic properties, they often introduce undesired drifts in target quantities or fail to sufficiently mitigate acoustic wave reflections.
This study introduces a modification of the NSCBC linear relaxation method, proposing a Non-Drifting and Non-Reflecting (NDNR) boundary condition framework. Building on the work of Daviller et al. [2], the NDNR approach is formulated as a dynamic system that integrates an Exponential Moving Average (EMA) pre-filtering of the QoI. This methodology effectively minimizes acoustic reflections while ensuring rapid response to numerical and acoustic disturbances. Theoretical and numerical assessments of the reflection coefficient show excellent agreement. Furthermore, this work presents a comprehensive theoretical and numerical analysis of the dynamic response of boundary conditions for both the NSCBC and NDNR linear relaxation methods. It enables the optimal selection of parameters: the relaxation coefficient K and the EMA cutoff frequency f_{c,τ_∞}. Through a combination of theoretical insights, numerical validation, and a 3D turbulent test case, the findings demonstrates the NDNR method's capability to rapidly achieve the desired mean flow while substentially reducing acoustic wave reflections.

References

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