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Streamwise-body-force-model for rapid simulation combining internal and external flow fields

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Abstract A streamwise-body-force-model (SBFM) is developed and applied in the overall flow simulation for the distributed propulsion system, combining internal and external flow fields. In view of axial stage effects, fan or compressor effects could be simplified as body forces along the streamline. These body forces which are functions of local parameters could be added as source terms in Navier-Stokes equations to replace solid boundary conditions of blades and hubs. The validation of SBFM with uniform inlet and distortion inlet of compressors shows that pressure performance characteristics agree well with experimental data. A three-dimensional simulation of the integration configuration, via a blended wing body aircraft with a distributed propulsion system using the SBFM, has been completed. Lift coefficient and drag coefficient agree well with wind tunnel test results. Results show that to reach the goal of rapid integrated simulation combining internal and external flow fields, the computational fluid dynamics method based on SBFM is reasonable.

1. Introduction

Topical research projects dealing with airframe and engines are usually treated as separate, independent endeavors. However, aerodynamic interactions of airframe and engines have increasingly attracted more attention over recent years. On one hand, aerodynamic performance analyses of aircraft are generally based on a clean airframe without a propulsion system. In fact, engines operating under various conditions would affect the aerodynamic performance of the aircraft. On the other hand, the inlet flow of the engines would be affected by the airframe surface, which brings a greater work demand to the engines. As such, the engines would no longer work at the design point, so the effects on aircraft aerodynamic performance should thus be estimated again. Under these aerodynamic interactions of the airframe and engines, it is difficult to estimate aircraft performance by conventional separated

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research. Therefore, many integrated numerical simulations have attempted to analyze the effect of aerodynamic performance under special flight conditions. Focusing on the influence on the external flow field caused by the inlet with high angles of attack, Murmann[1] simulated the full aircraft geometry of F/A-18, while the internal structures of the engine were ignored. Bissinger et al.[2] has shown the detailed analysis of flow in the inlet duct by simulation of the forebody and inlet. To study the inlet/fan interaction, Webster et al.[3] simulated a single inlet and turbofan stage without the airframe. However, integrated simulations of airframe and engines combining external and internal flow fields are infrequent.

With further study of aerodynamic interactions between airframe and engines, integrated aircraft/engine design will be the future trend,[4,5] especially for the new blended wing body (BWB) aircraft which is integrated with a distributed propulsion system on the top of the aircraft.[6,7] In this integrated configuration, the embedded engines are used to ingest the boundary layer that develops on the airframe boundary layer ingestion (BLI), which reduce wetted areas, ram drag and noise and ultimately reach the green goal for the next generation of civil aircraft design.[8–11] The subject interactions of the airframe and engines are more intimate, so integrated aircraft/engine design is essential. However, to achieve integrated design, the issue of integrated simulations must be solved, which are limited by their appreciable computing needs and convergence difficulties. It is well known that the internal structures of propulsion systems are extremely complex, and therefore, the core parts of the engines are independent in most aero-thermodynamic studies. The simulation of every core part requires considerable computing resources, especially those involving rotating machinery. Complex structures of blades and periodic rotations make the unsteady 3D numerical simulations for a whole compressor a difficult task. The clean airframe simulation also necessitates considerable computing resources, and therefore, the calculating quantities required for simulations which combine airframe with engines would be enormous. Furthermore, the convergence of this simulation combining external and internal flow would likewise be a challenge. Thus, to avoid extremely large calculation efforts, some simplified simulation methods have been put forward to help aircraft aerodynamic performance analysis. Mantič-Lugo et al.[12] analyzed the effects of the BLI propulsion system in transonic flow by using a uniform back-pressure boundary condition to replace fan faces in a 2D simulation. However, the real static pressure at fan faces is difficult to estimate, and the actual performance of the engines may deviate from the real working conditions given the highly distortions.

Kim and Liou[13,14] used a body force model developed from Gong's model[15,16] to simulate the N3-X hybrid wing-body configuration. With the infinite number of blades assumption of compressors, the blade forces could be modeled as normal and tangential forces to the local flow.[15] Adding the body force terms as source terms in aerodynamic equations, the turning and loss effects of the fan blades could be simulated, which achieved the integrated simulations. This approach was more accurate than the boundary condition method, while the procedure for generating the body force and the geometry generation of the mail-slot nacelle were comparatively complicated. For the integrated aircraft/engine design, optimization processes need iterative computations, which would likely induce a protracted design period as a result. Therefore, this subject approach was useful for prediction of aircraft performance but could not be widely used for the purpose of integrated aircraft/engine design.

To complete the rapid simulation combining internal and external flow fields, a further simplified yet reasonable body force model is presented via this research endeavor: streamwise-body-force-model (SBFM). The body forces are simplified to 1D terms paralleling of the streamline, and can be extracted more conveniently from the experimental data or CFD results. This new method (i.e., using the SBFM to simplify the simulation of compressors) could achieve the desired rapid integrated simulation, which combines the external and internal flow fields of the aircraft. Therefore, the aircraft aerodynamic performance could be estimated, and the aerodynamic interactions of airframe and engines could be assessed with this method. Moreover, this method could conserve appreciable computing resources; consequently it would be a fundamental research tool for integrated aircraft/engine designs. As such, the required elapsed period for optimal design could be greatly reduced.

Per the notions and assertions expressed above, the remaining balance of this research endeavor is hence organized as follows: Section 2 explains the derivation process of SBFM; Section 3 presents validation of this model in a low speed compressor and a transonic compressor; Section 4 provides simulation results for a BWB configuration by using the SBFM and then comparing these results with data obtained from wind tunnel experiments; Section 5 presents a summary and overall conclusion drawn from the acquired data.

2. Streamwise-body-force-model

2.1. Physical basis

Work done by the fans/compressors on flow increases the total pressure and total temperature. A simple axial stage is shown in Fig. 1, where c is the absolute velocity of flow, w is the relative velocity to rotor of flow and u is the tangential velocity of rotor. It is assumed that fluid flows into a fan or compressor along an axial direction, x-axis, and the employed physical basis is that rotors change flow direction while stators revert it back to axial, which ultimately means that the circumferential component of velocity is offset. In view of comprehensive

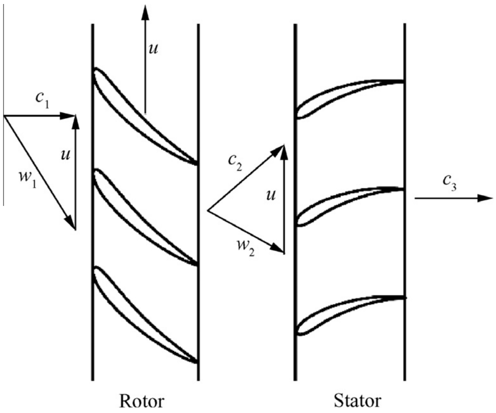

Fig. 1 Schematic of an axial stage.