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Development of the ball-spine inverse design algorithm to swirling viscous flow for performance improvement of an axisymmetric bend duct

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ABSTRACT

In the present study, the ball-spine inverse design algorithm is developed for swirling viscous flow regime to improve the performance of an axisymmetric 90-degree bend duct between the radial and axial diffuser of a centrifugal compressor. Performance improvement of the 90-degree bend duct is accomplished to increase its pressure recovery without separation. First, the effects of geometric parameters on flow separation are numerically studied and a safe margin is obtained for prevention of flow separation and stall. Then, the safe margin is enlarged to reach a higher pressure recovery via the shape modification of duct walls. The shape modification process integrates the BSA as shape modification algorithm and an axisymmetric flow analysis code as flow solver. Shape modification process is carried out by improving the current wall pressure distribution and applying it to the inverse design algorithm. Results show merits and robustness of the BSA for duct design in swirling viscous flow regime whereby the pressure recovery coefficient of the 90-degree bend duct increases up to 7%.

1. Introduction

Inverse design as an efficient approach is an attractive shape design method. In this method, the geometry is determined for a prescribed flow parameter such as velocity or pressure distribution. There are two different algorithms for shape design: non-iterative (coupled) and iterative (non-coupled).

In non-iterative methods, geometrical variables are applied to the governing equation and then, border is obtained directly. Because the coordination of border is a dependent variable in the governing equation, the governing equation is complicated. Although this method is usually limited to simple flow models such as potential flow, its computational cost is lower. Some studies have been done following this concept [1–5].

In iterative methods, flow and geometrical variables are independent. In these methods, a successive process including flow solving and shape modification is accomplished until convergence criterion is achieved. Although iterative methods have more computational cost, their governing equations are the same as used in numerical analysis. Thus, iterative algorithms can be used for complex geometries with complicated flow. Some of iterative methods are based on residual-correction algorithm. In this approach, the principal problem is to relate the difference between the current and target parameter (residual) to the required changes in the geometry. Some of iterative methods are based on optimization algorithms and some of them are physically based. However, convergence rate of shape modification process for physically based algorithms is higher. So these methods are more attractive.

One of the physically based methods is dominated by transpiration theory in which there is a normal mass flux on the surface. The difference between the target and current pressure distribution produces this flux. The geometry is updated at each iteration to remove non-zero normal velocity on the boundary (normal flux) [6–8].

Thompkins and Tong [9] proposed an inverse method based on the wall movement with a virtual velocity, calculated from the balance of momentum fluxes on the surfaces. This method was applied to 2D transonic compressor [10] and viscous flow [11].

Rahmati [12] used an inverse design method based on elastic membrane concept, which was first proposed by Garabedian and McFadden [13]. A new two-dimensional approach based on this concept was developed for the inverse design of a blade based on the specification of pressure loading distribution and blade thickness. In this method, the blade would deform as an elastic membrane under the pressure loading distribution. The pressure

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loading distribution was defined as the difference between the surface pressures on the two sides of the blade.

Safari et al. [14] proposed a novel inverse design method, called Elastic Surface Algorithm (ESA) for airfoil shape design in subsonic and transonic flow regimes. This method models the airfoil surface as an elastic beam that can be deformed due to the difference between current and target pressure distribution. The internal stresses are then set equal to zero in the modified shape and the process is repeated until the calculated pressure distribution converges to the target pressure distribution on the solid structure.

Mean average swirl distribution throughout the meridional plane is also a common inverse design specification which was first proposed by Hawthorne et al. [15]. The advantage of this specification is mostly apparent for turbomachinery design, where power is related to circulation distribution. A large number of studies have been developed following this concept [16–19].

Recently, a novel inverse design method called ball-spine algorithm (BSA) has been proposed by Nili et al. [20] for quasi-3D design of centrifugal compressor meridional plane. This method is based on the replacement of walls with virtual massive balls that freely move along the specified directions called spines. It has been applied for designing an axisymmetric diffuser [21] and for the impeller of a centrifugal compressor [22].

In the present work, the proposed BSA is developed for swirling viscous flow regime and then, the effect of swirl velocity (tangential component of velocity) on shape modification process is studied. Because of the important role of axisymmetric 90-degree bend duct (Ref. [23]) and its complexity, it is chosen as our case study. First, the performance of a bend duct is numerically obtained in the situation that swirl angle of viscous inflow is 60 degrees relative to the radial direction. Hereby, the effects of geometric parameters on flow separation are studied and a safe margin is obtained for prevention of flow separation and stall. Then, the wall pressure distributions of three bend ducts above the safe margin, having local flow separation on their inner wall, are improved to eliminate flow separation. The improved pressure distribution is applied to the BSA as the target parameter to improve the pressure recovery of the 90-degree bend duct. Finally, the safe margin is enlarged by inverse design and duct shape modification.

2. Numerical procedure

2.1. Geometry definition

The prescribed axisymmetric 90-degree bend duct is placed between the radial and axial diffuser of a centrifugal compressor. The meridional plane of centrifugal compressor with all its components is shown in Fig. 1. Moreover, the schematic of the 90-degree bend duct between the radial and axial diffuser with its parameters is shown in Fig. 2. Elliptical profile is used for inner and outer wall of the bend. Therefore, changes in cross section area versus the path length are linear.

2.2. Flow solver

In iterative inverse design methods, a shape modification algorithm is incorporated into a flow solver. At each shape modification step, flow field is solved to obtain wall pressure distribution. In the present study, a viscous 3-D code is used as the axisymmetric flow solver to decrease computational cost. In other words, the geometry and boundary conditions are modeled in a way that the flow is solved on an axisymmetric plane. It helps each flow numerical solution to be carried out in less than 50 seconds on a PC with an Intel(R) Core(TM) i7-26070QM CPU @ 2.20 GHz processor and 8.0 GB RAM. Numerical simulation uses only 14% of CPU. For this purpose, a thin sector of 90-degree bend with 0.1 degree thickness is chosen, so that only one element can be placed along its thickness. Then, rotational periodicity boundary condition is applied for two sides of the thin sector. Hereby, an axisymmetric flow can be analyzed. The prescribed sector is shown in Fig. 3. The 3-D flow solver code has been evaluated with experimental data before in reference [24]. The Reynolds-averaged Navier–Stokes equations (RANS) which describe the conservation of mass, momentum and energy are solved via a finite volume method. Pressure correction and momentum equations are solved as a couple. PISO algorithm is used for the combination of continuity and momentum equations to derive an equation for pressure correction. Second-order upwind discretization scheme is used for interpolation of variables, stored at cell centers, to the faces. The Reynolds stress terms in the momentum transport equations are resolved using shear-stress transport (SST) turbulence model, developed to blend the robust and accurate formulation of the k–ω model in the near-wall region with the free-stream independence of the k–ε model in the far field. The SST model was developed for the accurate prediction of aeronautics flows with strong adverse pressure gradients and separation based on Bourgeois et al. [25]. Flow is obtained for all the RMS residuals of momentum and energy of 10^{-6}.

Full 3-D numerical simulation of the 90-degree bend duct is accomplished and its results are compared with those of the thin sector. As shown in Fig. 4, the wall pressure distributions of the full 3-D 90-degree bend duct (at the angle of 0, 45 and 90 degrees relative to top of the bend duct) and the thin sector are completely matched. The difference of their pressure recoveries is also less than 2 percent. It demonstrates the precision and accuracy of the axisymmetric simulation.

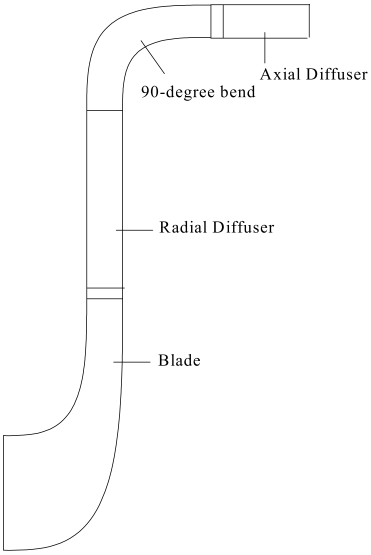

Fig. 1. Meridional view of centrifugal compressor and its stations.

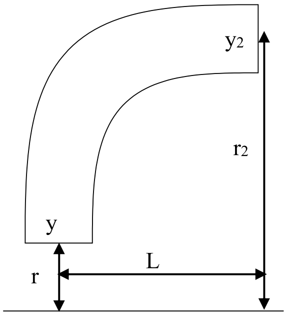

Fig. 2. Schematic of 90-degree bend duct and its parameters.