Multi-physics simulation of sand-erosion phenomena on turbine blade

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Abstract

This paper presents a newly developed numerical procedure to predict three-dimensional sand-erosion phenomena. It is well known that sand erosion is a typical multi-physics problem, i.e. turbulent flow field, particle motions and wall deformations, among others, interact. In the present code, in order to simulate this phenomenon, turbulent flow field, particle trajectories and amount of erosion on an eroded wall are calculated repeatedly. The gas-particle two-phase turbulent flow around a turbine blade is computed to clarify sand-erosion phenomena on the turbine blade. The numerical results indicate that sand erosion occurs severely around the leading edge and on the pressure surface, the rebounding particles cause the mechanical damage on the suction surface, and the aerodynamic performance deteriorates with proceeding sand erosion.

Keywords: Multi-physics simulation; Computational fluid dynamics; Sand erosion; Turbine blade; Three-dimensional computation

1. Introduction

Sand erosion is a phenomenon in which solid particles impinging on a wall cause serious mechanical damage to the wall surface. This phenomenon is a typical multi-physics problem in which the flow field, particle trajectory and wall deformation, among others, interact. It is well known that the performance and lifetime of various machines, such as aeroplanes, ships, gas turbines, pumps, and so on, are degraded severely due to sand erosion. In recent years, the sand-erosion phenomenon has been simulated numerically to protect industrial machines from mechanical damage. In these simulations, however, the change of the flow field and the relating particle trajectory during the erosion process were not taken into account. This treatment is physically unrealistic. Hence, we have developed a numerical procedure for the sand-erosion phenomenon, including the temporal change of the flow field and the wall shape. To simulate the phenomenon, the turbulent flow field, the particle trajectory and the amount of erosion on the eroded wall are calculated repeatedly. In computations of the flow field, compressible Navier–Stokes equations and a low-Reynolds-number type $\kappa - \epsilon$ turbulence model are adopted. Assuming that the concentration of suspended particles is dilute, then particle–particle collision and the influence of particle motions on the flow field are neglected. The Neilson–Gilchrist erosion model is used to estimate the weight loss due to erosion. This numerical code was applied successfully to a 90-degree bend, single airfoil, blade and particle separator [1,2]. However, this code was limited to two-dimensional conditions. Most sand-erosion phenomena occur in the three-dimensional flow field, and thus the application of the two-dimensional code is restricted by the geometrical problem. Therefore, the development of a three-dimensional code is needed in order to simulate more complicated configurations.

In the present study, considering the above-described background, we develop a numerical code to predict a three-dimensional sand-erosion phenomenon. Moreover, the gas-particle two-phase turbulent flow field around a turbine blade is simulated in order to investigate sand-erosion phenomena on the turbine blade surface and to verify the present code. The particle trajectories, the shape of the eroded blade surface, the static pressure and the total pressure loss coefficients are

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investigated numerically. It is shown that sand erosion occurs severely around the leading edge and on the pressure surface, the rebounding particles cause the mechanical damage on the suction surface, and the aerodynamic performance deteriorates with proceeding sand erosion.

2. Numerical procedures

The computational procedures are as follows:

1. Calculate the turbulent flow field with a Reynolds-averaged k-epsilon turbulence (RANS) model, proposed by Shimada and Nagano [3].
2. Calculate the particle trajectories and judge the collisions against a wall.
3. Estimate the amount of erosion using the Neilson and Gilchrist model [4,5] and change the wall shape.
4. Return to 1 if the wall shape is changed.

These procedures are repeated continuously until the computational time reaches the prescribed time. Since the sand-erosion phenomenon needs a long time period, the time scale of the abrasive process is much longer than that of the flow field, and thus the change of flow field could be regarded as a quasi-steady state. Therefore, steady-state flow distributions are thought to be valid for the eroded geometry and at every instance. This means that the phenomenon is mimicked as the series of quasi-steady states.

3. Computational conditions

In the present study, the developed code was applied to a turbine stator blade. The grid number in the flow field was $221 \times 62 \times 51$; that within the blade wall was $221 \times 60 \times 51$. The boundary conditions are imposed as follows: at the inflow boundary, the total pressure, total pressure and Mach number were 1.98×10^5 Pa, 382.2 K and 0.2, respectively. At the outflow boundary, the static pressure was 1.02×10^5 Pa. These values were the same as the experimental data. On the walls, no-slip and adiabatic conditions were imposed. At the side boundaries, a periodic condition was used.

It was assumed that the material of the solid particle that causes sand erosion was silicon carbide and its diameter was 100 μm. This condition is typical in a gas turbine operation. The blade material was assumed to be aluminium. Generally, aluminium is not used for turbine blades, but since ductile materials show a similar erosion pattern, we adopted aluminum to save computing time. When a particle was injected in the flow field, it was assumed that the particle velocity in the streamwise direction was the same as that of the gas phase, but other velocity components were assigned randomly to give random motion to a particle.

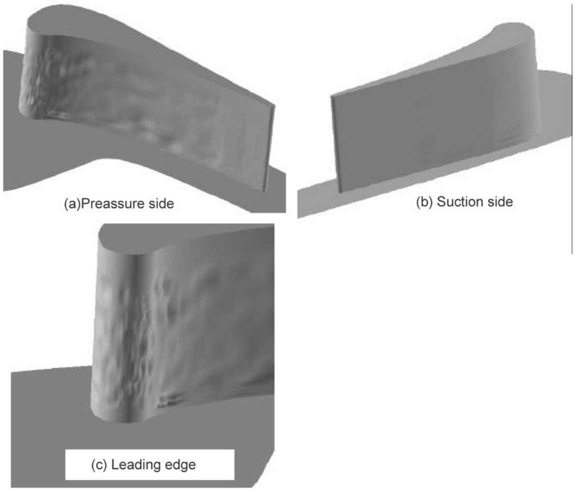

Fig. 1. Eroded blade.

4. Numerical results and discussion

The eroded blade obtained numerically is depicted in Fig. 1. We can see the highly rough surface, especially around the leading edge and on the pressure side. Moreover, although it is not so clear, we can see some mechanical damage on the suction surface. This tendency of sand erosion is ascribed to the particle trajectories (not shown here). These erosion characteristics are similar to those seen in the study by Tabakoff [6].

Fig. 2 exhibits the static pressure coefficients C_p along the blade at three different spanwise positions. Apparently, the sand erosion indicates a remarkable effect on the static pressure distribution along the blade surface. Moreover, it is interesting that the effect is stronger in the downstream half of the blade, where the mechanical damage is not so severe. This may suggest that the local influence of sand erosion on the aerodynamic performance is accumulated in the streamwise direction.

5. Concluding remarks

We developed a three-dimensional code to predict sand-erosion phenomena and applied it to a turbine stator blade. Through this study, we obtained the following insights:
(1) The highly rough surface due to sand erosion was reproduced successfully by our code. (2) Severe sand

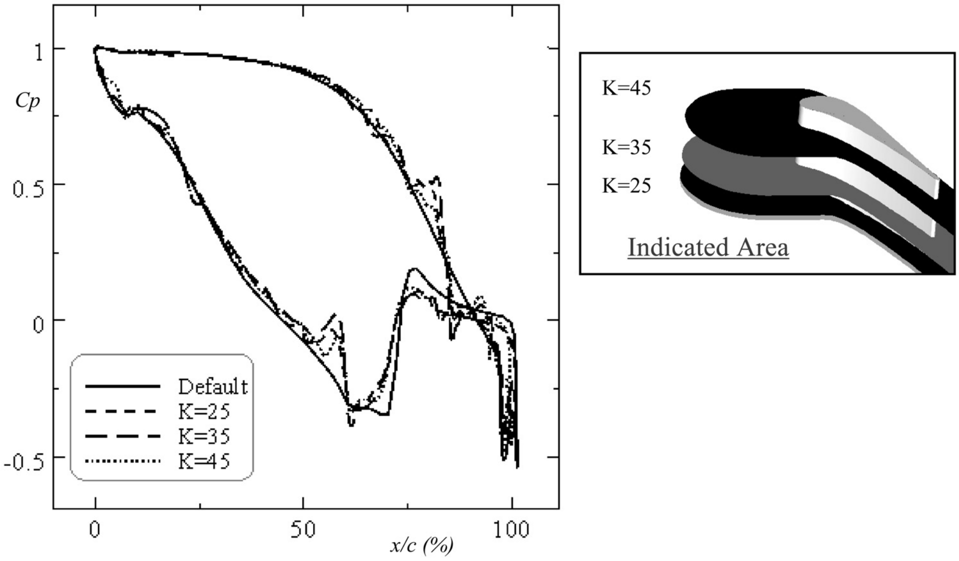

Fig. 2. Comparison of static pressure coefficients at different spanwise positions.

erosion occurs around the leading edge and the pressure side of the blade, and deformation wear is dominant in these regions because of the high impinging angle. (3) The rebounded particles on the pressure surface impact the suction surface and cause sand erosion there, but the damage is light due to the relatively small kinetic energy of the rebounded particles. (4) Aerodynamically, the remarkable effect of sand erosion was found in the downstream half of the blade. This may suggest that the sand-erosion effect accumulates along the blade surface. (5) Large and non-uniform total pressure loss was produced over the eroded surface.

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