Numerical prediction of aerodynamic performance for open geometry centrifugal compressor

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Abstract. Numerical prediction of aerodynamic performance of compressors has been widely performed by the RANS model, but there is the tendency to overestimate the work and efficiency of the impeller of a centrifugal compressor. In the RANS, we cannot analyze unsteady phenomena such as tip leakage flow. On the other hand, the LES models universal region of turbulence by performing spatial filtering operations. Since it does not include the concept of time averaging, it can be applied to unsteady calculations. In this paper we perform numerical prediction of aerodynamic performance by the RANS with the Spalart-Allmaras turbulence model and the LES with the Smagorinsky model, and reveal the unsteady phenomena, which cannot be analyzed by the RANS, by comparing each result. The CFD solver that we use is “UPACS”, which JAXA (Japan Aerospace Exploration Agency) has developed. We clarify its prediction accuracy and problem points of UPACS. The geometry data of the centrifugal compressor that we analyze is published in the papers written by Krain. The compressor is equipped with impeller with 24 full blades and vaneless diffuser. Comparing computed characteristic curves of mass-averaged total pressure, using the LES improves the overestimation of the total pressure ratio by the RANS by 10%. It seems that the LES can analyze the unsteady phenomena which the RANS cannot.

1. Introduction
Recently, centrifugal compressors are widely used for turbochargers for automobile and aircraft engines and have attracted attention. They are required to have a wide operation range in addition to high load and high efficiency. To improve the performance of centrifugal compressor it is necessary to understand its internal flow [1]. However, the centrifugal turbomachinery has the complicated geometric shape, so it is difficult to observe the detailed internal flow in experiments. Then, numerical prediction of aerodynamic performance has been widely performed by the RANS model, but there is the tendency to overestimate the work and efficiency of the impeller of a centrifugal compressor. In the RANS, we cannot analyze unsteady phenomena such as tip leakage flow and flow separation, and it seems that we do not consider the pressure loss caused by them.

In the past numerical analysis of turbulent flow fields, models including the concept of time averaging such as the RANS have been used in many cases. These can save relatively low computational costs. However, they are not suitable for a wide range of analysis targets because they often include many empirical constants, and have the disadvantage that they cannot handle strong unsteady phenomena. In recent years, the Large Eddy Simulation (LES) has attracted attention, and been used for many analysis targets. The LES models universal region of turbulence by performing spatial filtering
operations. Since it does not include the concept of time averaging, it can be applied to unsteady calculations. As an example where the LES is applied to flow analysis in a centrifugal compressor, in the study of HellStrom et al., analysis of unsteady flow near the surge of the centrifugal compressor, is performed [2].

In the turbomachinery industry, high accuracy flow analysis is required, but commercially available fluid analysis software has problems such as difficulty in expensive, large scale and high accuracy analysis and poor customization. The CFD solver “UPACS”, which JAXA (Japan Aerospace Exploration Agency) has developed and used for research and development of aircrafts, aeroengines and rockets, enables large-scale and high-precision analysis [3]. Therefore, UPACS may be expected to be used in the turbomachinery industry. Currently, JAXA is aiming to expand and improve UPACS to develop a package for turbomachines, especially centrifugal compressors.

In this paper we perform numerical prediction of aerodynamic performance by the RANS with the Spalart-Allmaras turbulence model and the LES with the Smagorinsky model, using UPACS, and reveal the unsteady phenomena, which cannot be analyzed by the RANS, by comparing each result. In addition, we clarify its prediction accuracy and problem points of UPACS.

2. Method

Figure 1 shows a photo of the centrifugal compressor used for the analysis. Geometry data for the compressor was published in the papers of Krain [4-7]. The compressor is equipped with a 30-deg backswept impeller and a vaneless diffuser of constant area. The specifications of this compressor are shown in Table 1. The calculations are performed at 100% of design rotation speed.

Table 1. Main parameters of the compressor [4-7]

| Parameter                          | Value (unit) |
|-----------------------------------|--------------|
| Impeller blade number             | 24           |
| Impeller exit diameter            | 400 (mm)     |
| Impeller exit height              | 14.7 (mm)    |
| Diffuser outlet diameter          | 600 (mm)     |
| Design speed                      | 22363 (rpm)  |
| Design rotor pressure ratio       | 4.7          |
| Design mass flow rate             | 4.0 (kg/s)   |

The mesh system is structured multi-block meshes. We use two types of computational grids, the total cells of which is 18M (Grid A) and 5M (Grid B), respectively. To guarantee a high quality of the mesh in regions around the impeller blade, O-blocks are used, whereas H-blocks are imposed in other regions. In order to analyze the tip leakage flow, blocks of tip clearance are installed on the calculation grid, and the density of grid points is increased. In the RANS, both Grid A and Grid B are used, and in the LES, Grid A is used.

The fluid flow solver is UPACS-LES developed by JAXA, which uses the cell-centered finite volume method. The governing equation is the compressible Navier-Stokes. Table 2 shows the calculation method used for steady calculations with the RANS model and unsteady calculations with the LES model. In the RANS, steady calculations with local time steps are performed, and in the LES, unsteady calculations are performed in time steps in which one pitch is divided into about 2500.
The boundary conditions are given as follows. The total temperature of the room and the total pressure of the atmospheric one are specified at the inflow boundary. The ratio of the static pressure at the outlet to the total pressure at the inlet is prescribed. The non-slip conditions are applied to the solid walls. In order to reduce the calculation cost, calculation is performed only for one pitch using periodic boundary conditions. The periodic boundary conditions are imposed on the green and light blue surfaces in figure 2.

| Table 2. Simulation method |
|-----------------------------|
| Solver                    | RANS   | LES    |
| Governing equation         | UPACS-LES | compressible Navier-Stokes |
| Spatial discretization     | cell-centered finite volume method |
| Convective terms           | Roe Scheme (2nd order) |
| Viscous terms              | 2nd order centered scheme |
| Time integration           | 1st order | 2nd order |
| Turbulence model           | Euler implicit | Euler implicit |
| SGS model                  | Spalart-Allmaras |

3. Results and Discussion
In this chapter, we show the results of calculations under the calculation conditions given in previous chapter, and discuss the results. The experimental data are taken from the paper of Krain [4-7]. In the steady calculations by the RANS, the convergence criterion is satisfied when the fact that residual of each physical quantity at the time step is about $10^{-3}$ smaller than the initial residual. On the other hand, the unsteady calculations by the LES are considered to converge when periodical fluctuations are observed in the flow rate at the compressor inlet and at the compressor outlet. As the calculation data, in the RANS calculation the time average value is acquired, in the LES calculation both the time average value and time series data are acquired. In the RANS, the converged solution is regarded as the time average value. On the other hand, in the LES, after the calculation is considered to converge, the calculation is further performed for two or more impeller rotations, and the average value is calculated based on the data. Simultaneously with the acquisition of the time average value, the time series data between one pitch is also acquired. For the initial value of calculation, the RANS calculation is performed with the initial value as zero, and the LES calculation is performed with the convergent solution of the RANS as the initial value. Since the LES calculation takes a considerable amount of time, the calculation is performed only under conditions such that the mass flow rate becomes around 4.0kg/s.

Figure 3 shows the compressor performance curve for total pressure ratio. The horizontal axis is the mass flow rate, and the vertical axis is the total pressure ratio between the inlet and the outlet of the compressor. The results of the LES are the time average data. With regard to the RANS, there was no significant difference between the results of calculations using Grid A and Grid B. At the mass flow rate of about 4.0kg/s, the total pressure ratio is overestimated about 6.9%. Also, the choke flow rate is overestimated. It is considered that the mass flow rate and total pressure ratio are overestimated because
secondary flow, which obstructs the flow in the compressor, cannot be captured. With regard to the LES, at the mass flow rate of about 4.0 kg/s, the total pressure ratio is overestimated about 6.2%. Compared to the RANS, the LES improves the overestimation of the total pressure ratio by 10%.

Figure 4 shows the performance curve for adiabatic efficiency. The horizontal axis is the mass flow rate, and the vertical axis is the adiabatic efficiency. Regarding the adiabatic efficiency, there is no significant difference between the results of calculations using Grid A and Grid B in the RANS. In the RANS, the adiabatic efficiency has a peak at the mass flow rate of around 4.6 kg/s. Compared to the experimental values, the calculation results of the RANS overestimate the mass flow rate as a whole, but the peak value of the adiabatic efficiency show good agreement. In the LES, at the mass flow rate of about 4.0 kg/s, the value of the adiabatic efficiency is almost the same with the experimental value.

Next, we compare the flow fields on the same span calculated with the RANS and the LES. The flow fields at mass flow rate of around 4.0 kg/s are compared. The results of the LES are the time average data. Figure 5 shows relative Mach number distributions on 90% span plane. The flow fields of both the RANS and the LES have high Mach number range near leading edge of impeller. Also, low Mach number regions are formed from the midstream to the downstream. It is conceivable that the low momentum fluid is accumulated near the shroud casing surface due to the centrifugal force and the interference of the blade tip leakage. While the low Mach number region of the RANS extends to the whole region, the low Mach number region of the LES is formed along the suction surface.

In order to capture the formation of vortices, we focus on the entropy distribution of the flow field. Entropy increase as vortices are created and mixed downstream with the surrounding flow. Therefore, the entropy distribution makes it easy to understand vortex formation. We use the entropy function \( S^* \) instead of the amount of entropy increase \( \Delta S \) [1]. The definition of \( S^* \) is as follows:

\[
S^* = e^{\Delta S/C_p} = \left( \frac{T_t}{T_{t0}} \right)^{\gamma/\gamma-1} \left( \frac{p_t}{p_{t0}} \right)
\]

(1)

where \( \Delta S \) is the amount of entropy increase, \( C_p \) is the specific heat at constant pressure, \( \gamma \) is the specific heat ratio, \( T_t \) is the total temperature, and \( p_t \) is the total pressure. Because \( S^* \) increases exponentially
with the increase of $\Delta S$, it is more suitable than $\Delta S$ as an index of energy loss that quantitatively indicates the generation process of vortices. Figure 6 shows entropy function distributions on 90% span plane. In the RANS, entropy rises overall from the middle to the downstream. In the LES, entropy rises along the suction surface. It can be seen that the region where the entropy rises corresponds to the low Mach number region in figure 5. Figure 7 shows entropy function distributions on 100% span plane. The high entropy region of the LES is larger than that of the RANS near the trailing edge on the pressure side. Therefore, it seems that the LES can capture vortices near the shroud casing.

![Figure 5. Relative Mach number distributions on 90% span plane (ṁ=4.0kg/s)](image1)

![Figure 6. Entropy function distributions on 90% span plane (ṁ=4.0kg/s)](image2)

![Figure 7. Entropy function distributions on 100% span plane (ṁ=4.0kg/s)](image3)
We observe the time history of the flow field calculated with the LES. The period ($T_p$) in which the impeller moves between one pitch is divided into five parts, and the flow field at each time is visualized. Figure 8 shows time history of instantaneous entropy function distributions on 90% span plane. Around the midstream, the high entropy region propagates from the suction side to the pressure side in the direction of the black arrow marked in the flow field at $t = 0$. The entropy of the region rises further by hitting the pressure side of the blade at $t = 4T_p/5$ (the brown circled region). Focusing on the area surround by the red circle, the high entropy region propagates from the pressure side to the suction side in the direction of the black arrow marked in the flow field at $t = T_p/5$. At $t = 2T_p/5$, the entropy further rises as the region approaches the suction side. This is consider to be because the vortices coming from upstream are mixed with the downstream vortices on the suction side. Figure 9 shows time history of instantaneous entropy function distributions on 100% span plane. Focusing on the area surround by the blue circle, the high entropy region propagates from the suction side to the pressure side in the direction of the yellow arrow marked in the flow field at $t = 0$. These high entropy regions are mixed, and the region with very high entropy spreads near the pressure side. It is considered that the tip leakage propagates to the pressure side, and many vortices are mixed near the pressure side and the entropy rises.

Figure 8. Time history of instantaneous entropy function distributions on 90% span plane ($\dot{m}=4.0\text{kg/s}$)

Figure 9. Time history of instantaneous entropy function distributions on 100% span plane ($\dot{m}=4.0\text{kg/s}$)
Three-dimensional visualization of the impeller flow is performed to capture the detailed vortex structure such as flow separation. In order to understand the vortex structure, we show the vortex cores by the eigenvalue analysis in the flow field [8,9]. By observing the vortex core, which is the center of the vortex, the size of the vortex flow can be known. Furthermore, the contour of the vortex core is represented by the non-dimensional helicity $H_n$, defined by the following equation;

$$H_n = \frac{\xi \cdot \omega}{|\xi| \cdot |\omega|}$$

(2)

where $\xi$ is the absolute vorticity vector and $\omega$ is the relative velocity vector [10]. $H_n$ indicates the direction of rotation of the vortices, and the vortices whose $H_n$ is 1 are longitudinal vortices around the right screw with respect to the flow direction, and vortices whose $H_n$ is -1 are longitudinal vortices around the left screw with respect to the flow direction. Figure 10 shows vortex cores and streamlines inside impeller. The LES captures more vortex cores than the RANS. As mentioned above, there are many vortex cores around the downstream suction side and around the downstream pressure side near the shroud. Therefore, the LES captures vortices that cannot be captured by the RANS, and the pressure loss is caused by the mixing of these vortices. This is considered to be the reason why the LES improves the overestimation of the total pressure ratio by the RANS.

![Figure 10. Vortex cores and streamlines inside impeller ($m=4.0$kg/s)](image-url)
4. Conclusion
We perform numerical prediction of aerodynamic performance for the centrifugal compressor by the RANS with the Spalart-Allmaras turbulence model and the LES with the Smagorinsky model, using UPACS. The main conclusions are as follows:

- The LES improves the overestimation of the total pressure ratio by the RANS by 10%.
- The region where the entropy rises corresponds to the low Mach number region.
- The high entropy region of the LES is larger than that of the RANS near the trailing edge on the pressure side. Therefore, the LES can capture vortices near the shroud casing.
- The tip leakage propagates to the pressure side, and many vortices are mixed near the pressure side and the entropy rises.
- The LES captures vortices that cannot be captured by the RANS, and the pressure loss is caused by the mixing of these vortices. This is the reason why the LES improves the overestimation of the total pressure ratio by the RANS.

5. References
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