EVALUATION OF DDES BASED ON SST $k$-$\omega$ MODEL WITH DIFFERENT SHIELDING FUNCTIONS FOR TIP LEAKAGE FLOW IN TURBOMACHINERY

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ABSTRACT

With the rapid development of computing power, hybrid RANS/LES is a new trend in engineering, which is more accurate than RANS when using a fairly refined mesh and at a lower cost than LES to achieve the same level of accuracy. As a widely used hybrid RANS/LES method, the delayed detached eddy simulation (DDES) is popular for treating premature activation of LES calculation within the boundary layer through introducing shielding function. However, it is still difficult to accurately predict the tip leakage flow (TLF) in turbomachinery. In the current study, the performance of DDES based on SST $k$-$\omega$ model with three different shielding functions are elaborately compared for the TLF in turbomachinery. The current research uses a flow model for the TLF in turbomachinery using a square duct with a longitudinal slit to reduce computational cost. Flow details, such as three-dimensional flow structures and the distribution of turbulent kinetic energy in different flow slices, are evaluated in comparison with LES results. Results show that DDES-SST method with all three kinds of shielding functions offers less unsteady flow features in the leakage flow region and the $F_2$ shielding function suppresses mostly in the small-scale turbulent structures of the TLF.

INTRODUCTION

Compressor is one of the most crucial components of aero-engine. Progressing the design of compressors to gain higher efficiency and higher loading performance is one of the most challenging goals in developing aero-engines. The main reason why high-performance compressors are difficult to design is that they have many types of complicated secondary flow structures inside (Horlock and Lakshminarayana, 1973; Taylor and Miller, 2017; Liu, et al. 2017; Liu, et al. 2019). The tip leakage flow (TLF) is a typical secondary flow in the flow passage (rotor passage), affecting the compressor's performance significantly (Denton, 1993). Since there is a pressure difference between the blade’s suction side and pressure side, the TLF is generated at the tip clearance, which can be simplified to a wall jet flow at the gap. The leakage flow and the main passage flow blend with each other, rolling up, forming three-dimensional vortex structures called the tip-leakage vortex (TLV) (Lakshminarayana, 1995). The TLV has a major impact on efficiency (Inoue et al., 1986), stability (Xie, et al. 2017), and noise generation (Hsiao, 2005), the mechanism of which needs to be further explored.

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The current research on the TLF mainly includes two methods: experiment and numerical simulation (Computational Fluid Dynamics, CFD). Through experiments, the actual flow information in the tip region can be obtained. In recent years, PIV and SPIV approaches have been applied to further observe and study the TLV and obtained progressive and novel results on axial compressors (Du et al. 2013; Li et al. 2017). However, the experimental method can only obtain part of the information of the flow field. It is hard to capture the whole three-dimensional instantaneous flow field using experimental methods. Thus, CFD has increasingly become an important tool for studying the aerodynamic problems of turbomachinery, which helps provide more flow field details. At present, the common CFD methods mainly include direct numerical simulation (DNS), large eddy simulation (LES), Reynolds averaged Navier-Stokes (RANS) method, and Hybrid RANS/LES method. RANS has been long used in engineering, but choosing an appropriate turbulence model is still an issue in RANS to deal with complex flows in compressors (Liu, et al. 2008; Liu, et al. 2016; Xie, et al. 2019). High fidelity methods, such as LES, have been successfully performed on a wide range of simple flows where traditional RANS or unsteady RANS (URANS) modelling cannot fully depict flow characteristics and physics to be consistently accurate (Tyacke et al. 2014). However, compared with RANS, using LES in high Reynolds number flow brings a heavy computational burden, and the strict requirements for grid size in LES computation (Choi and Moin, 2012) also hinders its wide range of applications to both academia and industry, especially for the internal flow in turbomachinery. Thus, hybrid RANS-LES methods are up-and-coming, considering accuracy and cost (Tyacke et al. 2019). The most widely used in engineering is Detached Eddy Simulation (DES), which is first proposed by Spalart (1997). It was found that when the DES was used in a fairly ambiguous grid in boundary layer, modelled-stress depletion (MSD) and grid-induced separation (GIS) occurred (Spalart, 2009). Thereafter, the Delayed DES method (DDES) was proposed to try to solve the “grey area” problem in DES by introducing a blending function to shield the boundary layer (Spalart, 2006). The feasibility and accuracy of DDES have been proved in turbomachinery engineering and research (Liu, et al. 2017; Liu, et al. 2019; Yan et al. 2018), but its shielding function’s performance is poor when simulating the TLF in compressors (Yamada et al. 2017). Furthermore, DDES should be improved to predict TLF more accurately in turbomachinery (Gao and Liu, 2020).

Recently, a flow model was proposed (Gao et al. 2019; Fang et al. 2019; Gao and Liu, 2019) to simulate the TLF in turbomachinery. Its ability to simulate the flow and turbulence characteristics in the TLF under various Reynolds number (Re) conditions has been proved. In this work, the performance of DDES based on the SST k-ω model with three different shielding functions are elaborately compared on the TLF model to evaluate the effect of different shielding functions. These studies can contribute to figuring out the weakness of the shielding functions and conduce to providing new suggestions for improving the accuracy of DDES in TLF.

**COMPUTATIONAL SETUP**

**Configuration of the TLF model**

As shown in Figure 1, the compressor blade passage can be simplified to a square duct with a gap on the top of one side wall (Gao and Liu, 2019), and the inflow(mainstream) in the model represents the axial flow in the turbomachinery, the distributed jet flow from the gap located on the top of the side wall resembles the TLF. Therefore, a tip leakage-like vortex is induced by the shear between the main flow and jet flow. The detailed sizes of the TLF model are summarized in Table 1.

![Figure 1 Geometry of the physical model](Gao and Liu, 2019).

<table>
<thead>
<tr>
<th>L_x</th>
<th>L_y</th>
<th>L_z</th>
<th>L_0</th>
<th>L</th>
<th>τ</th>
</tr>
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<tbody>
<tr>
<td>0.1m</td>
<td>0.1m</td>
<td>0.4m</td>
<td>0.1m</td>
<td>0.15m</td>
<td>3.5mm</td>
</tr>
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</table>

The entire computational domain has 7.2 million hexahedral cells, and there are 180 grids in pitch-wise(X) direction, 160 grids in spanwise(Y) direction, 250 grids in streamwise(Z) direction. The grid distribution of the X-Y plane is shown in Figure 2. In order to capture the finer flow structures in the tip region, the mesh is refined in the top wall-bounded region,
especially in the jet shear layer, which is illustrated in Figure 2. For DDES simulations, using the same mesh avoid the influence of mesh quality.

![Figure 2 Grid distribution of the X-Y plane in the physical model.](image)

In order to show the grid distribution in the refined region more clearly and illustrate that the mesh is fine enough for high-resolution simulations, Figure 3 shows the grid dimensionless length and numbers along the X or Y direction line (the dash-dot line in Figure 2). As shown in Figure 3(a), the refined region can divide into two stages; the first stage is the $X/L_x < 0.04$ including the tip region (slit width $\tau$), and the second stage is $X/L_x < 0.3$ covering the main TLV developing region. See Reference (Gao and Liu, 2019) for detailed discussions on the current mesh resolution.

![Figure 3 Grid dimensionless length and numbers along the X or Y direction line](image)

**Numerical methods**

A commercial software ANSYS Fluent 19.2 was used in these numerical simulations. Both LES and DDES are conducted. In the LES case, dynamic Smagorinsky-Lilly model (Germano et al. 1991; Lilly, 1992) is employed as the subgrid-scale model. The pressure-based implicit solver and PISO algorithm are chosen to deal with the incompressible governing equations. The momentum equations are discretized by second-order bounded central differencing scheme in both LES and DDES simulations, and selecting the second-order upwind scheme discretizes turbulence model equations in DDES simulations. About the temporal discretization, second-order implicit time integration with dual-time stepping is utilized. The SST k-ω model based DDES with different shielding functions is utilized for DDES.

The physical property of the fluid is set as air at 298K. Both density and molecular viscosity are constant. About the boundary conditions, the bottom wall is symmetrical. Apart from the bottom wall, the others are no-slip walls. Velocity inlet with specified velocity profiles is applied on the mainstream inlet and jet flow inlet. The Reynolds number is approximately $1.0 \times 10^5$, which is calculated based on the inlet velocity (10m/s) and slit length (0.1m). The outlet of the domain is defined as a pressure outlet, and its static pressure is set to 101325 Pa. The inlet flows’ velocity directions are normal to their respective boundaries. To generate the appropriate inlet turbulence, choosing spectral synthesizer method as the fluctuating velocity algorithm. The turbulence at the inlet is specified by turbulent intensity defining as 3.5% and the hydraulic diameter which is respectively calculated by inlet ($L_y$) and slit ($\tau$) sizes. More details about the settings can be found in Ref. (Gao and Liu, 2020).
The dual time-step method is applied for both LES and DDES computations. The physical time step is $2 \times 10^{-5}$ s and each physical time step has 30 inner iterations to meet the high-fidelity simulation’s requirement and make sure the local CFL number is not greater than 1. In order to obtain the credible time-averaging results, these quantities are time-averaged over 20,000 time steps after reaching a statistically stationary state, which is more than $26L/U_w$. $U_w$ is the reference velocity magnitude, defining as 10 m/s. As shown in Figure 4, the time-averaged quantities in LES have reached statistical convergence, and the numerical probe is located at the vortex core in $Z/L=40\%$ slice. Since the DDES simulation resolves fewer flow field details than the LES simulation, the statistics gained by the DDES simulation are more accessible to converge than LES. The statistics convergences of the LES and DDES simulations meet the requirements.

Figure 4 Statistical convergence result of first-, second-order momentum convergence history

DDES-SST WITH DIFFERENT SHIELDING FUNCTIONS

The original DDES-SST formulation is based on the DES-SST formulation of Strelets (2001). To alleviate the problem of grid-induced separation (GIS) (Spalart, 2009) in original DES, Menter & Kuntz (2003), and Spalart et al. (2006) proposed different shielding functions respectively: $F_d$, $F_1$, $F_2$, to guarantee that the modified DES model, DDES, could preserve the RANS mode in the wall-bounded region.

The governing equation of the DDES-SST model is very similar to the SST turbulence model for RANS in its form. The main difference is that the destruction term of the turbulent kinetic energy transport equation is modified for DDES-SST:

$$D_k = \rho \beta^* k_m \omega F_{DDES}$$  \hspace{1cm} (1)

where a DDES multiplier, $F_{DDES}$, is applied to enhance the dissipation in the free shear flow region, and then the turbulence viscosity work as subgrid-scale viscosity in this region. The DDES multiplier is defined as:

$$F_{DDES} = \max \left[ \frac{L_t}{C_{DDES} \Delta} (1 - F_{delay}), 1 \right]$$ \hspace{1cm} (2)

Where $\Delta$ represents the grid spacing:

$$\Delta = \Delta_{max} = \max(\Delta_x, \Delta_y, \Delta_z)$$  \hspace{1cm} (3)

$L_t$ is the turbulence length scale, and its expression is as follows:

$$L_t = \frac{k_m}{\beta^* \omega}$$  \hspace{1cm} (4)

$F_{delay}$ is the shielding function in the DDES-SST. It takes 1 in the wall-bounded region, which represents the RANS manner, and takes 0 in the separated region out of the boundary, making SST-DDES behave in the LES manner. There are three different forms of commonly used shielding functions: $F_d$, $F_1$ and $F_2$.

$F_d$ shielding function

The empirical shielding function $F_d$ is based on the parameter $r_d$, which is slightly modified relative to the SA model, and it is expressed as (Spalart et al. 2006):

$$F_d = \tanh((C_{d1} r_d) C_{d2})$$  \hspace{1cm} (5)

$$r_d = \frac{v_t + v}{\sqrt{U_{ij}U_{ij}} k^2 d^2}$$  \hspace{1cm} (6)
where \( \nu \) is the kinematic viscosity of molecular, \( \nu_t \) is the kinematic viscosity of turbulence, \( U_i \) is the velocity gradients, and \( \kappa \) is the Kármán constant which is equal to 0.41. Parameter \( r_d \) is equal to 1 in the logarithmic layer and gradually decreases to 0 at the boundary layer edge. In DDES-SST, \( C_{d1} \) and \( C_{d2} \) are suggested to be 20 and 3 respectively (Gritskevich, et al. 2012), which is different from the original DDES-SA.

**\( F_1 \) shielding function**

\( F_1 \) shielding function is one of the blending functions of the original SST turbulence model, which is expressed as follows:

\[
F_1 = \tanh(\phi^4) \tag{7}
\]
\[
\phi = \min(\max(\phi_1, \phi_2), \phi_3) \tag{8}
\]
\[
\phi_1 = \frac{500\mu}{\rho \nu d^2} \tag{9}
\]
\[
\phi_2 = \frac{4\rho k_m \sigma_{22}}{CD_{k_w} d^2} \tag{10}
\]
\[
\phi_3 = \frac{\sqrt{k_m}}{0.09 \omega d} \tag{11}
\]
\[
CD_{k_w} = \max\left(\frac{2\rho \sigma_{22}}{\omega^2}, \frac{\partial k_m}{\partial x_i}, \frac{\partial \omega}{\partial x_i}, 10^{-20}\right) \tag{12}
\]

Where \( d \) represents the distance to the wall.

**\( F_2 \) shielding function**

Same as \( F_1 \) shielding function, \( F_2 \) also comes from the original SST model. It is defined as follows:

\[
F_2 = \tanh(\phi^2) \tag{13}
\]
\[
\phi = \max(2\phi_3, \phi_1) \tag{14}
\]

Where \( \phi_3 \) and \( \phi_1 \) are the same as the above formula.

**RESULTS AND DISCUSSION**

**Flow Features of the Averaged Flow Field**

**Distribution of Shielding Function**

The shielding function can control the switch between RANS and LES modes. When it is equal to 1, it represented that the DDES is carried out in a RANS manner. When it takes zero, the shielding function is invalid, and the DDES is converted to LES mode. The distributions of shielding functions in different Z slices are shown in Figure 5, which could visually reflect the employment of RANS or LES. In general, the main part of the computational domain behaves in the LES branch of DDES.

![Figure 5 Distribution of shielding functions in different Z slices](image-url)
Figure 6 shows the distribution of different shielding functions in $Z/L=40\%$ slice perpendicular to the streamwise where the primary vortex begins to twist and deform with the generation of ring-formed induced vortices.

![Figure 6 Distribution of shielding functions in $Z/L = 40\%$ slice (40\% slit length)](image)

**Figure 6 Distribution of shielding functions in $Z/L = 40\%$ slice (40\% slit length)**

When the value of the shielding function is between 0 and 1 (mainly the green zone), it is expressed as the switching zone from the RANS region to the LES region. The distribution of each shielding function tends to be 1 in the wall-bounded region to ensure that the RANS mode dominates the region. However, the shielding effect of each shielding function is different. Obviously, the shielding effect of $F_2$ is the most significant, and it has the largest switching zone (the green zone). $F_1$ has the smallest protection range (the red zone), and the consequent RANS region is also the smallest. The shielding effect of $F_d$ is between the other two. Although the RANS region of $F_d$ is about the same size as the RANS region of $F_2$, and the switching zone of $F_d$ is clearly smaller than $F_2$, which illustrate $F_d$ achieves faster switching from RANS to LES than $F_2$. The large switching zone of $F_2$ may eventually affect the accuracy of DDES to resolve TLF.

**Flow Properties in Flow Slice**

The vortex form and intensity can be indicated by vorticity analogously. The vorticity distributions are illustrated in Figure 7 and Figure 8 by the mean streamwise vorticity, which can represent the property of the primary vortex.

![Figure 7 Distribution of mean streamwise vorticity in different $Z$ slices](image)
As shown in Figure 7, the vortex intensity is underestimated at the early stage of vortex evolution in DDES results. The slice of $Z/L=20\%$ is selected in Figure 8, a very typical slice at the early stage of vortex evolution, showing the negative vorticity underestimation.

**Figure 8 Distribution of mean streamwise vorticity in $Z/L = 20\%$ slice (20\% slit length)**

The strong negative vorticity can be observed at the vortex core; however, the induced vortex has positive vorticity adjacent to TLV. The intensity of streamwise vorticity predicted by DDES with $F_2$ shielding function is much weaker, while the vorticity intensity predicted by the DDES with $F_1$ is similar to the DDES with $F_d$, which is stronger than DDES with $F_2$. The negative vorticity in the vortex core region of the LES result is significantly strongest, which is rarely predicted by DDES with different shielding functions, indicating that the current DDES still requires improvement to predict TLF accurately.

**Figure 9 Distribution of mean pressure in $Z/L = 20\%$ slice (20\% slit length)**

In the TLV core region, a sharp pressure drop appears to maintain the rotation, and the pressure drop can also reflect the TLV intensity, which could be used to evaluate the precision and fidelity of simulation. Figure 9 illustrates the distribution of mean pressure in $Z/L=20\%$ slice. Compared with Figure 8, The strong negative vorticity region coincides with the low-pressure region. Both negative vorticity and pressure drop could characterize local vortex intensity. In general, all three DDES-SST simulations with different shielding functions underestimate the low-pressure region in the vortex core. Similarly, the lowest pressure value of DDES with $F_2$ is apparently smaller than the other two DDES cases, which means that $F_2$ shielding function further underestimates the intensity of the TLV.

**Turbulence Characteristics**

**Comparison of Turbulent Viscosity Ratio**

The vortex structure identified by Q-criterion (Hunt et al. 1988) is shown in Figure 10. At the early stage of the TLV, between $Z=0.1m$ and $Z=0.14m$, both LES and DDES simulations resolve the primary vortex which is a large-scale structure in this flow field. After $Z=0.14m$, the ring-formed induced vortices are generated around the primary vortex, but the DDES simulations have lost many small-scale turbulent structures compared with LES simulation. In general, DDES-SST simulations with all three kinds of shielding functions offer less unsteady flow features in the leakage flow region and the $F_2$ shielding function suppresses primarily in the small-scale structures of the TLF, especially when the primary vortex loses stability and begins to deform. Additionally, in Figure 10 (c), the turbulent viscosity ratio on the primary vortex of the TLV is higher than it in Figure 10 (a),(b), and too large turbulent viscosity ratio hinders the generation of turbulent pulsations eventually, resulting in the delayed bursts of LES content. The turbulent viscosity ratio of LES is significantly lower than the DDES results, so excluding the influence of shielding functions, DDES still has specific problems to resolve TLF.
Figure 10 Instantaneous vortex structures visualized by the iso-surfaces of $Q=2\times10^6$/s$^2$, and colored by turbulent viscosity ratio, the jet is from $Z=0.1$m to $Z=0.25$m ($Z/L = 0\sim100\%$)

As known, based on the “equilibrium” assumption (the balance of production and dissipation terms in turbulent transport equations), the LES branch of the DDES can be simplified to a static Smagorinsky-Lilly subgrid-scale model. Compared Figure 10 (d) with (e), the turbulent viscosity ratio on the primary vortex ($Z<0.15$m) of the TLV calculated by LES-DSM is lower than the LES-SSM. However, both LES simulations can capture more small-scale turbulent structures than DDES simulations, illustrating that the LES branch of DDES cannot perform as well as the static Smagorinsky-Lilly model. In general, when the “equilibrium” assumption may not hold in complex three-dimensional flows, such as the TLF, the LES branch of DDES is not very credible and solid.

Figure 11 Distribution of the Dynamic $C_s$ value in LES-DSM simulation

In the static Smagorinsky-Lilly model, $C_s$ is a static constant set to 0.1 in ANSYS Fluent, which can get not bad results in a wide range of simple flows. However, the static constant also limits its adaptive ability to simulate complicated flows. Figure 11 illustrates the distribution of the dynamic $C_s$ value in LES-DSM simulation, which is various from 0 to 0.23. Although the dynamic coefficient varies widely, the results shown in Figure 10(d)(e) have no significant difference, especially the value of turbulent viscosity ratio. Excluding the effect of SGS model on the results, the leading cause for the deficiency of DDES is how to convert to LES branch correctly in various complex three-dimensional flows.

Comparison of Turbulent Kinetic Energy

The unsteady small-scale structures of the flow in the TLV are also of great significance, especially in downstream. The instability of the primary vortex results in the formation of vortex structures in different scales, and the turbulent motions of these vortices also have a large scale range, which brings challenges to turbulence simulation. Turbulent kinetic energy distribution could reflect the local unsteady characteristics. In this study, turbulence field in the LES simulation is represented by the resolved TKE, which is defined as:

$$k = \frac{1}{2}(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}) \quad (15)$$

In DDES, the turbulence field is represented by the total TKE which consists of three parts, including the modelled TKE, the resolved TKE, and another part due to the discretization error:
\[ k_T = k + k_m + k_e \] (16)

Where \( k_m \) is the modelled TKE. It could be obtained from the TKE transport equation in DDES-SST. \( k_e \) represents the discretization error (numerical error), which is much smaller than the other two parts in high-fidelity simulation. Thus, this small quantity \( k_e \) can be ignored in this work.

The development process of total TKE (or resolved TKE of LES) in the TLV with different Z slices is shown in Figure 12. Compared with the result of LES, the results of DDES with different shielding functions all have different degrees of delay for the generation of turbulent pulsations, and the total TKE in the core region of TLV is underestimated. Among all three DDES results, the result of DDES with \( F_2 \) is the most seriously underestimated, and the result of DDES with \( F_1 \) or \( F_d \) are similar.

![Figure 12 Distribution of total TKE in different Z slices](image)

The distribution of total TKE could illustrate the effects of flow unsteadiness, especially in the turbulent region. Figure 13 displays the distribution of total TKE in \( Z/L = 60\% \) slice, where the turbulence in the vortex region is fully developed.

![Figure 13 Distribution of total TKE in \( Z/L = 60\% \) slice](image)

The TKE distribution predicted by LES shown in Figure 13(d) has been proved to be a typical turbulence structure in the TLV by experiments (Du et al. 2013; Li et al. 2017) and high-fidelity numerical simulations such as DNS and LES (Fang et al. 2019; Gao et al. 2019), thus it could be used as an evaluation criterion. Compared with the LES result, total TKE in the vortex core of TLV is underpredicted in DDES results. Among them, the result of DDES with \( F_2 \) illustrates that the total TKE in the vortex core of TLV is the most severely underestimated, and there is a low-value area of TKE on the right side of the vortex core, indicating that its unsteadiness is the weakest and the vortex core is the most stable.
Furthermore, there is also a relatively high-value area of TKE on the left side of the vortex core in Figure 13(c), which is different from the others, indicating that $F_2$ shielding function causes serious deviation in the DDES calculation. The total TKE of DDES with $F_1$ or $F_d$ have high values in the TLV core region, while the positions of vortex core are relatively lower than LES. The total TKE of DDES with $F_3$ at the vortex core is slightly higher than that of DDES with $F_d$.

The distribution of total TKE and Reynolds normal stresses could reflect the anisotropy of the Reynolds stresses in a way. Since the turbulence in the vortex region is fully developed, the $Z/L=60\%$ slice is selected for further analysis. In Figure 14, the distribution of total TKE and Reynolds normal stresses are displayed. In the LES result, there are two peaks, corresponding to the TLV core and the shear layer outside of the vortex. Obviously, the TLV core at $Y=0.02m$ where $v'v'$ is the largest term, and $u'u'$ is the second. Both $v'v'$ and $u'u'$ are at the peak, which represent the wandering and unsteadiness of the vortex core, showing that the velocity fluctuations are mainly in the spanwise and pitch-wise directions. Compared with the LES result, the vortex core of both DDES with $F_d$ and DDES with $F_1$ nearly at $Y=0.02m$ where the peak of total TKE is lower than LES. However, the vortex core of DDES with $F_2$ is at $Y=0.015m$ where both $v'v'$ and $u'u'$ are smaller than $w'w'$ which means it cannot get the right turbulence structure.

![Figure 14 Distribution of total TKE and Reynolds normal stresses along a pitch-wise line (X=0.013m) crossing the vortex center in $Z/L=60\%$ slice](image)

The ratio of resolved TKE in total TKE can reflect whether the LES branch works in the region of concern. Because the mesh is fine enough for LES simulation, the ratio can achieve over 0.9 as expected in the full field except for the boundary layer. Nevertheless, Figure 15 shows that the ratio only meets 0.6 in the shear layer between mainstream and jet, illustrating that the LES branch of DDES does not activate in time. Furthermore, the ratio of DDES with $F_2$ is smaller than the other two, especially in the shear layer, which results in the underestimation of the resolved turbulence. Since the $F_2$ shielding function in the TLV region is too conservative, the RANS region is too large and ultimately avoids the generation of velocity fluctuation, making the resolved turbulent kinetic energy accounted for relatively low.

![Figure 15 Ratio of resolved TKE in total TKE in $Z/L=60\%$ slice (60\% slit length)](image)

Turbulence Energy Spectra

Figure 16 shows the turbulence energy spectra of velocity fluctuations at the monitoring points located at the vortex core in different flow slices where the primary vortex has been losing stability, and unsteady flow fluctuations have been generated. The turbulence energy spectra in Figure 16 show an inertial subrange generally conforming to a slope of $-5/3$. Apparently, the turbulence energy spectra predicted by all three DDES with different shielding functions are lower than the LES, indicating that apart from the effect of the shielding functions, the DDES method still has the problem that it is challenging to capture multi-scale turbulence accurately.
In the low-frequency region, especially near the $f = 100\text{Hz}$, there is a significant drop in DDES results, indicating that the DDES simulations fail to capture the large-scale unsteady motion of TLV. The previous work (Gao and Liu, 2020) shows that the underestimations of $u$ and $v$ fluctuation dominate this drop, and the frequency of the drop roughly corresponds to the wandering frequency of the TLV (wandering in X-Y plane), which You (You et al. 2007) mentioned. Additionally, as shown in Figure 16(a),(b), the turbulence energy spectra of DDES are much smaller than that of LES in the high-frequency region. Thus, it could not resolve the abundant small-scale turbulence structures particularly. Furthermore, the shielding functions also have an impact, especially the $F_2$, which make its turbulence energy spectra lower than the other two shielding functions.

![Figure 16 Turbulence energy spectra at the vortex core(f/Hz)](image)

CONCLUSIONS

A simplified tip leakage flow (TLF) model is used to evaluate the performance of DDES based on SST $k$-$\omega$ model with different shielding functions, which are compared with the LES results. The flow features of the averaged flow field, unsteady flow characteristics and turbulence characteristics are compared in detail. The main conclusions are listed as follows:

1) The shielding effect of the $F_2$ shielding function is the most deficient. Unsteady flow fluctuation is suppressed partly due to overly conservative partitioning of too large switching zone of RANS, resulting in the delayed generation of LES content and offering less unsteady flow features in the leakage flow region. In addition, it cannot get the right turbulence structure in the vortex core where the turbulence is fully developed.

2) The shielding effect of $F_1$ and $F_d$ are slighter than $F_2$, and they could predict the flow properties more accurately than $F_2$, capturing more small-scale turbulent structures. Specifically, the protection range of $F_1$ is smaller than $F_d$, while the performance of $F_1$ and $F_d$ in resolving the flow unsteadiness is similar.

3) Comparing with LES result, the total TKE in the vortex core is underestimated in DDES results, and each of DDES with different shielding functions offers less unsteady flow features in the leakage flow region, indicating that many details of the flow field are missing in the DDES results. At the early stage of vortex evolution, DDES with different shielding functions rarely predicts the pressure drop and negative vorticity in the vortex center. Thus DDES method still has drawbacks, and the grey area problem has not been entirely solved by adding a shielding function.

TLF and the mainstream have intense mixing and shearing effects, forming the TLV and the rapid burst of turbulent pulsations often starts in the protected RANS zone or switching zone. Apart from the effect of the shielding functions, the DDES method still has the problem that it is difficult to capture multi-scale turbulence accurately. Therefore, it is necessary to investigate further the advanced modifications (based on various mechanisms) in DDES and try to grasp the critical mechanism so that the DDES model can switch quickly and reasonably fill turbulent pulsations in the proper region and avoid forming the non-physically induced separation at the same time.

NOMENCLATURE

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<td>TLF</td>
<td>Tip leakage flow</td>
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<tr>
<td>TLV</td>
<td>Tip leakage vortex</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle image velocimetry</td>
</tr>
<tr>
<td>SPIV</td>
<td>Stereoscopic particle image velocimetry</td>
</tr>
<tr>
<td>$L_x$, $L_y$, $L_z$</td>
<td>Sizes of the flow model [m]</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the slit [m]</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Width of the slit [mm]</td>
</tr>
<tr>
<td>$X$, $Y$, $Z$</td>
<td>Cartesian coordinates [m]</td>
</tr>
</tbody>
</table>
RANS Reynolds averaged Navier-Stokes $x^+,y^+,z^+$ Non-dimensional turbulence wall distances
LES Large-eddy simulation $Q$ Second invariant of velocity gradient [s$^{-2}$]
DNS Direct numerical simulation $\mu$ Molecular viscosity [kg/(m·s)]
DDES Delayed detached-eddy simulation $\omega$ Specific dissipation rate [s$^{-2}$]
TKE Turbulent Kinetic Energy $\Omega_z$ Mean streamwise vorticity [s$^{-1}$]
DSM Dynamic Smagorinsky-Lilly model $f$ Frequency of turbulent energy spectra [Hz]
SSM Static Smagorinsky model $\rho$ Density [kg/m$^3$]
u, v, w Velocity of X, Y, Z direction [m/s]
k$_T$, k$_m$, k Total, modelled, and resolved Turbulent kinetic energy [m$^2$/s$^2$]

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References


