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主 論 文 の 要 旨

論文題目　**Direct numerical simulation on turbulent/non-turbulent interface in compressible turbulent boundary layers (圧縮性乱流境界層中の乱流・非乱流界面に関する直接数値計算)**

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論 文 内 容 の 要 旨

Turbulent boundary layer (TBL) widely exists in many engineering applications and geophysical flows. E.g., the development and separation of turbulent boundary layer can significantly affect the lift, drag, and also the instability of aircrafts and vehicles. Turbulent boundary layers are known as highly intermittent flows, where both turbulent and non-turbulent (laminar) fluids coexist. In the last few decades, many researches show that there is a thin layer that separates the turbulent and non-turbulent flows in the intermittent region, which is called turbulent/non-turbulent interface (TNTI). The flow properties, such as enstrophy, kinetic energy dissipation, and scalar concentration, sharply change in this layer so that they are adjusted between the turbulent and non-turbulent flows. This layer is also important for the exchanges of substance, energy, and heat between turbulent and non-turbulent flow and is also related to the spatial development of turbulence. Therefore, it is very important to understand the characteristics of TNTI. The spatial distribution of turbulent fluids also plays an important role in scalar mixing in TBLs. Modeling of turbulent mixing is crucial in numerical simulations of reacting flows and combustions.

Understanding the characteristics of the TNTI is greatly important in modeling and predicting the spatial development of turbulence as well as the flow control based on the turbulent structures near the TNTI. Even through there already exist some direct numerical simulation (DNS) studies on the TNTI in TBL, there are still some questions which are not yet addressed:

- The grid setting has not been evaluated with the consideration of the resolution on the TNTI in TBL. Since the most DNS studies for TBL focus on the near-wall region, where the grid spacing are carefully considered, grid spacing for accurately investigating the intermittent region has not been fully considered.
- The TNTI has been extensively studied in recent studies on free shear flows and some similar characteristics of the TNTI are also found in the TBL. However, there are less studies on the TNTI in the TBL than in free shear flows, and the entrainment process near TNTI layer in TBL remains unclear.
- Although a high-speed regime is of great importance in aerospace engineering applications, most studies on the TNTI have been done in incompressible flows. The TNTI in compressible turbulence is still less understood compared with the one in incompressible flows.

As described above, it is important to investigate the TNTI in compressible TBLs. In this Thesis, temporally developing DNSs with two types of grid setting are performed for both the subsonic and supersonic turbulent boundary layers in order to investigate the spatial resolution effects on TNTI, compressibility effects, entrainment process, as well as the development of the high-speed turbulent boundary layers.

In Chapter 1, the research background and motivation of the study are introduced.

In Chapter 2, the numerical methodology and computational conditions for temporal DNSs are described. DNSs with two types of grid setting are performed in order to investigate the spatial resolution effects on TNTI.

In Chapter 3, the fundamental characteristics of DNS data for temporally developing boundary layers are shown, including the comparison with theoretical laws, experimental data, and spatial DNS data.

- Excellent agreements can be found for first- and second-order statistics in present DNSs with fine and coarse grids with previous studies of theoretical law, experimental data, and spatial DNS data for a comparable value of Re_θ, where Re_θ is the Reynolds number based on the momentum thickness. The comparisons show that the temporal DNS performed here accurately replicates the compressible TBLs for both grid settings.

- The compressibility effects do exist for the thermodynamics properties, and it becomes more significant for higher Mach numbers. The peak of turbulence production is found to be located at the buffer layer. However, the compressibility is weak so that the compressibility does not change the turbulence structures significantly even for $M = 1.6$.

In Chapter 4, the way of TNTI layer detection is described, then, the spatial resolution of DNS and compressibility effects on the TNTI layer are discussed.

- The irrotational boundary (the outer edge of the TNTI layer) is detected as an isosurface of vorticity magnitude. The mean thickness of the TNTI layer and inner sublayers, i.e., viscous super layer (VSL) and turbulent sublayer (TSL), are evaluated by computing the conditional mean vorticity and enstrophy transport equations.
- The detected TNTI layer shows that the grid resolution near the TNTI in DNSs with a course grid (based on previous studies) is insufficient to resolve the smallest scale of turbulence near the TNTI, which results in a thicker TNTI layer. In contrast, the results on TNTI with a fine grid are close to previous studies in free shear flows and shear free turbulence. The mean thicknesses of the TNTI layer, VSL, and TSL are found to be around $15\eta_{TI}$, $4\eta_{TI}$, and $11\eta_{TI}$, respectively, where η_{TI} is the Kolmogorov scale in turbulent region near the TNTI layer.
- The compressibility effects increase with Mach number. However, the conditional statistics confirm that the direct influences of compressibility are small near the TNTI layer even for Mach number M = 1.6.

In Chapter 5, the physical mechanism of the entrainment process in compressible TBLs are investigated with a fine grid resolution.

- The irrotational boundary frequently propagates toward the non-turbulent region and hardly propagates toward the turbulent region. It is also found that the propagation velocity is dominated by the viscous effects.
- The mean downward velocity is found for the non-turbulent flow in the intermittent region, which is consistent with spatially developing TBLs. The mass entrainment rate per unit horizontal area of the temporal TBLs is also found to be consistent with the theoretical prediction for the spatial compressible TBL, and also with experimental data for a spatial incompressible TBL at Mach number $M = 0.8$. It is confirmed that the dominant mechanism for the momentum transport is not

different between spatial and temporal compressible TBL.

- The mass flux within the TNTI layer is studied by the mass transport equation in the local coordinate system moving with the outer edge of the TNTI layer. It is shown that the mass within the VSL is transferred toward the TSL in the direction normal to the TNTI, while the TSL is dominated by a tangential transfer. The result is also compared with the single vortex model for incompressible flows. The mass flux predicted by this model within the TNTI layer agrees well with the statistical result, which strongly suggests the connection between the entrainment process within the TNTI layer and the small-scale vortical structures found underneath the TNTI layer of the turbulent boundary layers.
- The passive scalar mixing near the TNTI is studied for investigating the entrainment process. The highest conditional mean scalar dissipation rate appears near the boundary between the VSL and TSL. This indicates that the fluid locally entrained from non-turbulent side encounters the fluid coming from the turbulent side, where the difference in the passive scalar between these fluids creates large scalar gradients. Both visualization and conditional statistics show the dependence on the TNTI orientation for the scalar dissipation rate and the production rate of scalar gradient, both of which have a large value near the leading edge facing the downstream direction than the trailing edge facing the upstream direction.

In Chapter 6, the real-world data circulation (RWDC) and the relation with the present study are explained. In addition, the contributions of this work to the society is also discussed.

The final chapter summarizes the Conclusion. Some future prospects are also introduced and discussed.

This work contributes to the understanding of the TNTI in the compressible TBLs. Based on the DNS data for the compressible TBLs with two types of grid setting, a reasonable grid setting for studying the TNTI study in compressible TBLs is evaluated. The compressibility effects on TNTI and the physical mechanism of the entrainment in compressible TBLs are investigated and discussed.