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論　　文　　名	「Instability and breakdown of supersonic streamwise vortices(超音速縦渦の不安定性と崩壊に関する研究)」
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論文要旨

In high-speed flows, the growth of perturbation is suppressed. This is called the ``compressibility effect'', and it means that the growth characteristic of perturbations (i.e., instabilities) decreases as the Mach number increases. In addition, since the propagation of perturbations is limited by the finite speed of sound in supersonic flows, small-scales are not easily produced and sustained, in contrast to subsonic flows. Reduced communication between disturbances in high-speed flows has been researched as a possible physical source of the stabilizing effect of compressibility. The stabilizing effect is thought to prevent the initial roll-up and eventual pairing of spanwise (or azimuthal) vortical structures. For this reason, mixing of the fuel and oxidizer is a major barrier to realizing supersonic combustion ramjet (scramjet) engines for airbreathing hypersonic aircraft. Until now, mixing layer studies have been widely researched and compressibility effects in mixing layers have been estimated by introducing convective Mach numbers. At high compressibility, the dominant instability waves are oblique, tending toward three-dimensional structures. According to many experiments, specifically, streamwise vorticities induced by three-dimensional waves, which grow from perturbations in

turbulent mixing layers, jets, and wakes, seem to relax the compressibility effects. These findings strongly indicate that streamwise vorticities in supersonic flows have an advantage in a mixing process. However, the basic instability properties of streamwise vortices in supersonic flows remain unknown. In addition, there is a lack of comprehensive understanding of compressibility effects because the essentially physical quantity involved in the effects has not yet been specified. It is, thus, of fundamental importance to investigate transition processes of supersonic streamwise vortices. The purpose of the thesis is to elucidate the instabilities of supersonic streamwise vortices and mechanism of compressibility effects. In this thesis, the author has organized a series of studies on the transition processes of supersonic streamwise vortices obtained from the linear stability theory, asymptotic analysis, and numerical simulations.

The remainder of this thesis is organized as follows:

Chapter 1 presents background information on the study of the supersonic streamwise vortices stability and an overview of the thesis, which comprises five major investigations given in Chapters 3--7. The instability characteristics of supersonic streamwise vortices have been organized in detail.

Chapter 2 defines a basic flow in supersonic streamwise vortices with axial velocity deficits, which is assumed to be steady and axisymmetric. In this thesis, the Batchelor vortices are adopted as compressible streamwise vortices because the profiles are consistent with measurements in supersonic flows at high Reynolds numbers. Previous measurements have shown that the stagnation temperature profiles of supersonic streamwise vortices are approximately constant.

In Chapter 3, the inviscid instability conditions of compressible streamwise vortices have been derived as general instability conditions of swirling flows, using asymptotic analysis with large wavenumbers for the disturbance equation. Based on the nature of this instability, the obtained growth rate can be justifiably classified into four-types and can be described using an entropy instability term, a spiral instability term, a helicity instability term, and an acoustic instability term. The entropy instability term correlates with the compressibility. The spiral instability term is reasonably expressed by the axial and azimuthal velocities, and their wavenumbers. The helicity instability term depends on the helicity profiles. In particular, the unstable condition for wake-type flows is satisfied when they possess a negative helicity in the profiles. The acoustic instability term depends on the local speed of sound. This classification is consistent with previous works on axial flow with jets and provides a reasonable interpretation of the instability of swirling flows (streamwise vortices).

In Chapter 4, the spatial instability characteristics of streamwise vortices with various Mach numbers are investigated using inviscid linear stability analysis. This study found that the growth rate of vortices at the uniform stagnation temperature is smaller than that of isentropic vortices, which are often adopted as standard model vortices. The instability characteristics of the streamwise vortices can be explained using the ratio of the circulation to the axial velocity deficit, and also with the Mach number. Moreover, it is found that the compressibility effect is caused by the negative energy arising from the entropy gradients of supersonic vortices that accompany the axial velocity deficit--like wake. From an energy perspective, the effect may be reasonably correlated with the large density perturbations in supersonic flows. This thesis also proposes a general convective Mach number for supersonic streamwise vortices. The normalized growth rates are shown to be a function of the convective Mach number within the investigated range of ratio parameters.

Chapter 5 describes numerical formulations for three-dimensional simulations in order to simulate the disturbances developed in the supersonic streamwise vortices during the early transition stage. The governing equations and numerical methods, which can capture the instabilities and transition characteristics with high accuracy, are introduced in the chapter. Numerical simulations are conducted excluding the effects of turbulence models from the static pressure of the vortex center and velocity deficit.

In Chapter 6, spatially developing processes in supersonic streamwise vortices have been investigated for various Mach numbers. Although instabilities in streamwise vortices depend on the profiles across the flow, even if the flow is initially linearly unstable, the effects of perturbations on the nonlinear evolution remain unknown. It is, therefore, necessary to clarify the response to small random perturbations in linear and nonlinear states. For vortices with uniform stagnation temperatures, the calculated spatial evolutions show that a bending wave mode is excited and spiral structures of low-wavenumber modes only develop downstream for small swirl parameters. In contrast, for swirl parameters larger than the moderate amount (approximately 0.5), relaminarization occurs downstream. This thesis also found that the relation between the circulation and the freestream Mach number contributes to a necessary condition determining whether perturbations can grow in supersonic flows. For isentropic streamwise vortices, instability properties at high Mach numbers are comparable to those in low-speed flows because the evolution can give rise to high-wavenumbers within the core. The resulting entropy instability is analogous to the Rayleigh--Taylor instability and has the advantage of being insensitive to compressibility effects in supersonic flows.

To overcome problematic compressibility effects, the fifth section of this chapter focuses on compound vorticity fields formed by an axial and azimuthal vorticities in streamwise vortices, related to the helicity instability in Chapter 3. At high Mach numbers, streamwise vortices with uniform stagnation temperatures are affected by the compressibility, as shown in Chapter 4 and in Section 4 of Chapter 6. From the perspective of transitions, the spatial development of processes in the compound vorticity fields are studied at Mach number 5.0 (hypersonic flows). A large vorticity thickness greatly enhances centrifugal instability, with the consequent development of perturbations with competing wavenumbers outside the vortex core. During the transition process, the streamwise vortices can generate large-scale spiral structures and a number of hairpin-like vortices. Remarkably, the transition causes a dramatic increase in the total fluctuation energy of hypersonic flows because the negative helicity profile destabilizes the flows because of the helicity instability. The unstable growth that might be related to the correlation length between the axial and azimuthal vorticities of the streamwise vortices is also demonstrated. These findings have a suggestion for the utility of deriving absolute instability conditions in supersonic flows that has been unexplored.

Chapter 7 deals with another vortex breakdown that is not caused by natural transitions. Since streamwise vortex breakdown occurs when the vortex interacts with shockwaves, the prediction of the onset of supersonic vortex breakdown during interaction in both internal and external flows is important. This thesis proposes a theoretically derived criterion for predicting the onset of supersonic vortex breakdowns during interactions between an oblique shockwave and a streamwise vortex. This criterion involves two inequalities: first, derived from the net pressure difference between the shock and the kinetic energy following the shock, and second, requiring that the product of the circulation and the freestream Mach number (i.e., the azimuthal Mach number) be greater than unity. The vortex breakdowns of three-dimensional numerical simulations are reasonably determined by time-averaged fields provided that multiple pressure-increases occur and helicity disappears behind the oblique shockwave along the line of the vortex center. The predicted breakdown conditions are consistent with the numerical results at Mach numbers 2.0 and 3.0. This study found that although little attention has been given to the axial velocity deficit for shock-induced vortex breakdowns, the deficit is important for classifying breakdown configuration.

Finally, conclusions are presented in Chapter 8.

The major results are as follows:

(i) the general convective Mach number for supersonic streamwise vortices has been proposed to evaluate compressibility effects, (ii) in terms of natural transition processes, the findings that streamwise vortices with unstable entropy can generate breakdowns with only limited influence from the compressibility, and vortices with negative helicity lead to a high destabilization in supersonic flows, and (iii) a criterion for the shock-induced breakdown of a streamwise vortex is reasonably derived from the two simple inequalities. Therefore, this thesis provides some findings on supersonic streamwise vortices and useful indicators for promoting difficult transitions in supersonic flows using streamwise vortices introduced into the flows.

審査結果の要旨

一般に、流れの速度が速くなると流れに含まれる変動成分の成長は抑えられる。特に、流れが超音速になるとその傾向は顕著になる。極超音速機（マッハ 5 以上の飛行速度）や宇宙往還機に用いられることが期待されるスクラムジェットエンジン（超音速燃焼ラムジェットエンジン）では、燃焼器の中の流れが超音速となり、燃料の混合をいかに速やかに行うかかが課題である。これは、いわゆる超音速混合問題としてこの分野では広く認識されており、超音速時に乱れの成長が抑制されるメカニズムの解明と、混合促進のための様々な燃料噴射形態が提案されてきている。その中で、混合促進を行う手法の一つとして、流れ方向に軸を持つ縦渦の利用が提案され、その実効性が実験的に確認されている。本研究は、そのような背景のもと、さらに、この超音速縦渦の効果を高めるため、超音速縦渦の不安定性：超音速縦渦で形成される剪断層の発達に関連（主流との混合促進)、崩壊：大規模乱流構造から微細構造への遷移（非線形問題）を数値的に検討したものである。
得られた主な結果は以下のとおりである。
（1）　超音速縦渦の不安定性について、解析的に検討し、その不安定は、エントロピー不安定、旋回不安定、ヘリシティー不安定、音響不安定の 4 つの不安定モードに分けられる。
（2）　線形安定性の議論から、不安定性は、循環と軸方向速度欠損の比、マッハ数に依存する。このように循環と軸方向速度欠損の比に不安定性が依存することは、実際のスクラムジェットエンジンの設計に対して重要な指針であること、さらに、圧縮性の効果についても、縦渦内のエントロピー分布が影響すること。
（3）　超音速縦渦の発達と崩壊の数値シミュレーションから、超音速縦渦の非線形発達が線形安定性理論の予測通りに起きることを確認するとともに、エントロピー不安定がレイリー・テイラー不安定に類似しており、超音速縦渦の不安定性に重要な役割を果たしている。
（4）　衝撃波と超音速縦渦の干渉による渦崩壊を数値的に検討し、渦崩壊を引き起こす衝撃波の強さにはある閾値がある。

以上，要するに，本研究は，これまで未解明であった超音速縦渦の不安定性と崩壊現象を解析的、数値的研究し、発達・崩壊に影響するパラメータとその影響を明らかにしたもので、圧縮性流体力学の研究に多大の寄与と今後の研究の方向性を示すものであるとともに、スクラムジェットエンジンの開発に重要な示唆を与えるものである。すなわち、航空宇宙工学や圧縮性流体力学の発展に貢献すること大である。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。学位論文審査委員会は、本論文の審査ならびに学力確認試験の結果から、博士（工学）の学位を授与することを適当と認める。