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学 位 論 文 題 目	Study of High-Order Unstructured Grid Method for Aerodynamic Simulation Using Spectral Volume Discretization（スペクトラルボリューム離散化に基づく高次精度非構造格子空力解析法の研究）
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論 文 内 容 要 旨

The modern computational fluid dynamics (CFD) methods can easily consider various complicated geometries such as complete aircraft configuration even with high-lift-devices (HLD) fully deployed by using unstructured grids. Unstructured grid methods have offered flexible grid generation for 3D complicated geometries, and extend the applicability of CFD in real aircraft design cycles. Despite the progress made in CFD, there are still many practical problems for which reliable prediction with a high level of sustained accuracy is difficult. Vortical flow fields are especially challenging even for latest CFD solvers. One numerical issue has been considered as critical for the conventional unstructured grid solvers in practical use that the spatial accuracy of the commonly used finite volume method remains at best second order even in smooth regions. It is well recognized that low-order numerical methods require extremely fine grid resolution to preserve the vortical flow structures due to excessive numerical diffusion inherent to the numerical methods. In order to resolve and preserve important flow features without intensive computational efforts, low dissipative high-order methods are required. The severe resolution requirements in the use of advanced turbulence model such as detached eddy simulation (DES) and large eddy simulation (LES) could be also alleviated by the possible application of high-order numerical methods.

In conventional finite volume method for unstructured grids, high-order reconstruction of dependent variable is attempted by extending the stencil to nearby cells. Because unstructured grid generally lacks smoothness, the reconstructed

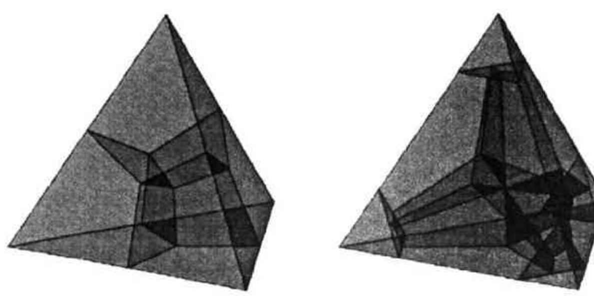

Figure 1　Partitions in a tetrahedral SV (Linear: $p1$, Quadratic: $p2$).

dependent variables are sensitive to local grid quality, and are usually less accurate than what is expected. For this reason, achieving the formal order of accuracy is never an easy matter for unstructured grid methods. Recently, new high-order unstructured grid methods such as discontinuous Galerkin (DG) method, spectral volume (SV) method and spectral difference (SD) method have attracted attention. As an important common feature, these methods introduce degrees of freedom within each element for high-order approximation to the solution and are expected to achieve the formal order of accuracy even on unstructured grids. Due to its local character, these methods are very suitable for local *h/p* adaptation techniques and are highly parallelizable.

Despite the advantages and capabilities of the new trend of high-order unstructured grid methods mentioned above, these methods are not yet mature and current implementations are subject to strong limitations for its applications to large scale industrial problems. In this study, we aim at overcoming the existing limitations and shortcomings of higher-order unstructured methods and explore the potential for robust and efficient applications in the aeronautical industry. In order to develop a high-order unstructured grid method for aerodynamic simulation, the SV method is employed as the discretization framework. The SV method belongs in a class of Godunov-type finite volume method. Each spectral volume (SV), which is usually the same as the traditional triangular or tetrahedral finite volume, is further subdivided into structured subcells called control volumes (CVs) (Fig. 1). Cell-averaged data from these CVs provides the stencil for high-order polynomial reconstruction within each SV.

One of the major shortcomings of high-order unstructured grid methods is the increasing of computational costs. It is imperative to develop efficient implicit solution schemes for high-order methods, especially to obtain steady state solutions. In this study, an efficient implicit lower-upper symmetric Gauss-Seidel (LU-SGS) solution approach has been applied to the high order SV method for unstructured tetrahedral grids. The LU-SGS solver is preconditioned by the block element matrix, and the system of equations is then solved with a LU decomposition. The compact feature of SV reconstruction facilitates the efficient solution algorithm even for high order discretizations. The developed implicit solver has shown more than an order of magnitude of speed-up relative to the Runge-Kutta explicit scheme for typical inviscid (Fig. 2) and viscous problems.

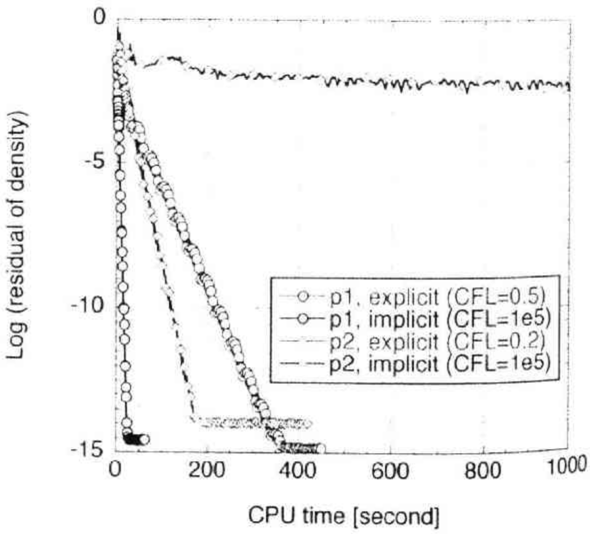

Figure 2 Comparisons of convergence histories between the explicit and implicit schemes for the inviscid flow over a bump.

Another key problem in high-order methods is the preservation of monotonicity across discontinuities such as shock waves. In order to maintain the numerical stability near discontinuities, some data limiting process is necessary. To preserve monotonicity across discontinuities without reducing the high-order accuracy in smooth regions and deteriorating the convergence to steady states, an efficient and robust limiting approach has been developed for the SV method. Distributions of state variables near discontinuity are limited as the weighted sum of the element averaged value and unlimited reconstruction while invoking the monotonicity principle. For the steady linear advection problem, the present limiter has shown substantial improvement in both the magnitude of error and the order of accuracy compared with the conventional slope limiter. Then the developed method is tested for typical transonic (Fig. 3) and supersonic problems by solving the Euler equations and improved accuracy and convergence has been demonstrated.

For accurate prediction of aerodynamic performance in high-Reynolds number flows, we certainly need to account for turbulent effects. In this study, an aerodynamics simulation code for the Reynolds averaged Navier-Stokes (RANS) equations is developed using the SV method for unstructured tetrahedral meshes. The turbulent viscosity is modeled by the Spallart-Allmaras (SA) one-equation model. The developed scheme is validated for turbulent flow over a flat plate and assessed for transonic flowfield over a wing compared with available CFD results. Then, the developed flow solver is applied to obtain complicated flows over high-lift devices. By comparing obtained results with the corresponding experimental data and the available numerical results, the capability to predict complicated flowfields has been favorably shown. And the applicability to large scale industrial problems has been also indicated (Fig. 4).

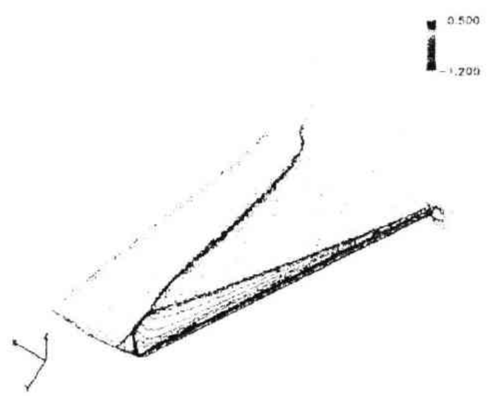

Figure 3 Pressure coefficient contours on the ONERA-M6 wing using *p*2 approximation.

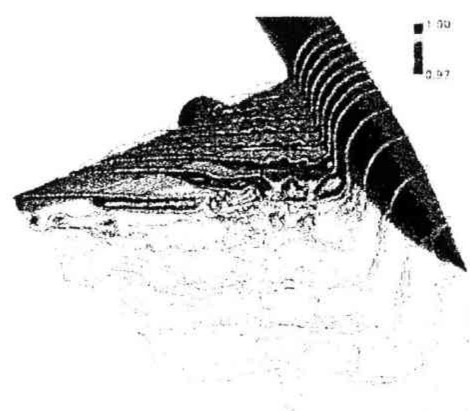

Figure 4 Total pressure ratio contours around a civil transport model in high-lift configuration using *p*1 approximation.

論文審査結果の要旨

数値流体力学(Computational Fluid Dynamics; CFD)は，航空機の空力形状設計の初期段階で最適形状探索に用いられるとともに，設計点におけるさまざまな空力特性の取得に多用され，航空機開発における空力設計技術に大きな変革をもたらしている。しかし，設計点から外れた飛行条件や，離着陸時の高揚力装置を展開する渦流れ場の解析では，CFD の解析精度は低く風洞試験による確認が必須とされている。航空機の開発コストの更なる低減を実現するには，より信頼性の高い CFD 手法の確立が要求されている。複雑な航空機形状に適合可能な非構造格子法で高次精度が達成可能な手法として，近年，計算セル内に自由度を設けてその時間発展よりセル内の物理量分布を再構築する新しい計算手法が提案されている。その一つである Spectral Volume (SV)法は，従来の有限体積法の自然な拡張であり，早期の実用化が期待されているが，収束特性に優れた陰解法が構築されておらず，大規模な数値解析も実施されていない。本論文は，SV 法に適した効率的な陰解法の構築に関する研究成果をまとめたものであり，全編 5 章からなる。

第 1 章は緒論であり，本研究の背景，目的および構成を述べている。

第 2 章では，効率的な陰解法を実現するために，非線形 LU-SGS 法を用いた陰的 SV 法を構築している。線形移流方程式に対する定式化を示して安定性と収束性を検証した後に，圧縮性粘性流れ場へ拡張され，良好な収束特性を有することが示されている。また，物体表面形状の高次精度表現を組み入れた境界条件を用いると，非粘性流れ場の数値誤差を劇的に低減できることを示している。これらは，陰的 SV 法の構築に対する有益な成果である。

第 3 章では，高次精度計算手法の安定性と収束性に重要な勾配制限関数について述べている。計算セルを複数の Control Volume (CV)に分割して内部自由度を割当てる SV 法では，計算セル内の分布を線形分布に置き換える通常の勾配制限関数を用いると，CV の値が大きく変化するために収束性を著しく損なう場合がある。計算セル内の分布を大きく変えることなく数値的な安定性を実現する簡単な勾配制限法を新たに提案し，その有効性を示している。これは高次精度 SV 法の実用化において，非常に重要な知見である。

第 4 章では，開発された SV 法を用いて，三次元翼周りや高揚力装置を展開した航空機形状周りの圧縮性粘性流れ場の解析を行い，計算手法の検証を行っている。得られた空力係数や圧力分布は，より多くの計算セルを用いた有限体積法の解析結果に遜色無く，SV 法の高い精度を具体的に示している。高揚力装置を展開した航空機半截模型周りの流れ場解析では，高揚力装置から生じた縦渦が下流域まで伸長していく様子がきれいに捉えられており，SV 法に期待される非構造格子上での高次精度の達成が具体的に示されている。これは，SV 法の実用化に向けた重要な成果である。

第 5 章は結論である。

以上要するに本論文は，SV 法の陰解法の構築とともに，新たな勾配制限関数の提案ならびに陰的 SV 法を用いた大規模計算の実現を示すものであり，航空宇宙工学および数値流体力学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。