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論文内容要旨

It is conjectured that wall erosion at the nozzle throat of a solid rocket motor (SRM) is caused by complicated turbulent effect. In order to have the throat diameter unchanged throughout the burning period, solid rocket motors employ thermo-resistive materials at the nozzle throat. On the other hand, thermo-insulative materials are used to protect the nozzle wall upstream/downstream of the throat region from head load. The nozzle surface made of different materials recesses in different rates in the burning period, and forms a backward-facing step at the joint in the downstream of the throat. This backward-facing step causes boundary layer separation, which reattaches in the downstream side of the step where shock waves as well as a number of strong longitudinal vortices appear. The surface recession is supposed to be enhanced by the interaction of these longitudinal vortices with the wall surface. This nozzle erosion mechanism, however, is poorly understood because of the lack of experimental data. Daimon et al. examined the role of longitudinal vortices in surface erosion by the three dimensional Reynolds-averaged Navier-Stokes (RANS) simulation of the flowfield in SRM. However, it seems that RANS approach can smear out such longitudinal vortices interacting with the wall surface. Therefore, a time dependent and highly accurate numerical simulation of the turbulent flowfield over the entire nozzle region is certainly needed.

In practical engineering problems, large eddy simulation (LES) is one of the major techniques used to predict turbulent flowfields. LES directly resolves eddies in the flowfield larger than the computational mesh size. The eddy structures smaller than the mesh size are dissipated according to subgrid scale (SGS) model. This approach has successfully reproduced the energy spectrum for three-dimensional homogeneous turbulence. However, it is difficult to find a rational SGS model when one applies LES to complicated flowfields such as compressible turbulent flowfield involving solid particles that appears in SRM applications. No universal SGS model is yet known, and hence a suitable SGS model should be constructed for each problem that we may consider.

Implicit LES approaches, on the other hand, have broad applicability to complicated turbulent flowfields, because they do not need any specific SGS models. In the monotonically integrated LES (MILES) proposed by Boris et al. the flux corrected transport (FCT) algorithm is used as a monotonicity preserving higher order scheme. Besides the molecular viscosity, the numerical viscosity inherently involved in the scheme is shown to dissipate the shortest wavelength component of numerical oscillations associated to the given mesh system. As a result, MILES can give a reasonable energy spectrum of homogeneous turbulence with a natural truncation occurring at the maximum wavenumber. According to the concept of MILES, monotonicity preserving higher order schemes for compressible flows such as the monotone upstream scheme for conservation law (MUSCL), essentially non-oscillatory (ENO) or weighted ENO (WENO) reconstruction should be able to replace FCT.

Recently, the compact schemes have attracted attention as suitable numerical schemes for direct numerical simulation (DNS) and LES, because they can achieve higher spatial accuracy using relatively narrow stencils. Although traditional compact schemes have only dispersive error, the modern compact schemes with biased interpolation do possess dissipative property. However, these modern compact schemes with biased interpolation are not necessarily suitable for implicit LES, because they are not monotonicity preserving schemes. In order to achieve monotonicity preserving property, Deng et al. developed the weighted compact nonlinear scheme (WCNS) in which WENO like weighted technique was introduced in biased interpolation. WCNS is one of the higher order monotonicity preserving schemes which can stably capture shock waves. It is noted that the weighted interpolation in WCNS corresponds to a fifth order biased interpolation in smooth flowfield, and also to a third order WENO like interpolation at discontinuities.

Implicit LES computations using Kawamura-Kuwahara scheme are well known. In such studies, various flowfields including complicated engineering applications have been successfully obtained. However, in spite of successful examples, implicit LES has not been received widespread acceptance in the turbulence modeling community because of the lack of a theoretical basis for justification of implicit LES approach. Therefore, besides the study for establishing such theoretical basis, what we can do is to compare the computed flowfield using implicit LES in detail with that given by DNS or ordinary LES, to indicate possible evidences that implicit LES really works for computing turbulence.

The ultimate purpose of the present work is to develop an implicit LES code which can solve the complicated turbulent flowfield involving both shock waves and solid particles at the nozzle throat of SRM, and try to identify the erosion mechanism. Before doing so, we obviously need to examine whether WCNS is really suitable for implicit LES of turbulent flowfield. In the present thesis, therefore, we aim to develop an implicit LES code using WCNS and explore the applicability of the developed method for turbulence research. First, we develop an implicit LES method using WCNS for computing 1D Burgers turbulence. The Burgers turbulence can be regarded as 1D model equation of 3D Navier-Stokes equations. The computed result of Burgers turbulence exhibits triangular waves which are nonlinearly developed from the initially smooth wave shapes. It is known that the inertial range of the energy spectrum for Burgers turbulence is in proportion to k^{-2} due to the presence of triangular waves. This property is often utilized to verify newly developed spatial filters and SGS models for LES. The obtained results are compared with DNS and conventional LES utilizing dynamic eddy viscosity model. The computed energy spectrum obtained by the conventional LES shows a non-physical bump due to dispersion error at higher wavenumber region, while that given by the present implicit LES duplicates the energy spectrum obtained by DNS up to higher wavenumber region. A natural truncation of the energy spectrum occurs at high wavenumber limit without any non-physical bump. It is shown that the implicit LES using WCNS provides the amount of numerical viscosity just needed to suppress numerical oscillations and also to give the energy spectrum that reproduces the DNS result fairly well.

Next, a two-dimensional homogeneous turbulence is first obtained by solving the Navier-Stokes equations for incompressible flows. We compare the inertial range in the computed energy spectrum with that obtained by DNS and also those given by the different LES approaches. From the computed energy spectra, it is shown that both the implicit LES utilizing WCNS and another implicit LES utilizing fifth order compact scheme give the energy spectra that agree fairly well with that of DNS. A truncation of energy spectrum occurs naturally at high wavenumber limit indicating that dissipative effect is included properly in the present approach. On the other hand, the conventional LES utilizing high order central difference scheme for the convective terms and also the dynamic SGS model shows significant numerical oscillations. A linear stability analysis for WCNS indicates that the third order interpolation determined in the upwind stencil introduces a large amount of numerical viscosity to stabilize the scheme, but the same interpolation makes the scheme weakly unstable for waves satisfying $k\Delta x \approx 1$. In the computed result of homogeneous turbulence, a fair correlation is shown to exist between the locations where the magnitude of $\nabla \times \omega$ becomes large and where the weighted combination of the third order interpolations in WCNS deviates from the optimum ratio to increase the amount of numerical viscosity. Therefore, the numerical viscosity involved in WCNS becomes large only at the locations where SGS viscosity can arise in ordinary LES. An implicit LES code utilizing WCNS is also developed to solve the Navier-Stokes equations for compressible flows, and the same homogeneous turbulence is solved. The computed results are slightly more dissipative than the corresponding incompressible case, but the computed energy spectrum shows the appearance of inertial range and also the natural truncation of the energy spectrum.

Finally, an implicit LES method using WCNS for general curvilinear coordinate systems in three-dimensional space for compressible flows is developed. We solve a supersonic flow over a backward-facing step using the developed code. In order to promote turbulent transition in the recirculation region, white noise is superimposed to the streamwise velocity component at the location slightly upstream side of the step. Various flow features pertinent to the supersonic flow over a backward-facing step, such as the boundary layer separation at the backward-facing step, an emergence of shock wave along the reattachment line, and a recirculation region behind the step, are clearly captured. It is shown that the surface pressure profile behind the step agrees reasonably well with the corresponding experimental data, though the pressure just behind the step is over predicted and onset of the pressure rise in the recirculation region is slightly delayed. From the critical examination of the flowfield, it is shown that the flowfield behind the step is certainly turbulent, although whether the turbulence is fully developed or yet immature is difficult to be determined. The computed result obtained in the present study shows a potential applicability of the present implicit LES utilizing WCNS to various complicated flowfield involving both shock waves and turbulence.

論文審査結果の要旨

Large Eddy Simulation (LES) は，ナビエ・ストークス方程式の直接解法とレイノルズ平均方程式に対する解法の間を埋める実用的な乱流解析手法として注目されている。LES では，格子解像度以下の小さな渦成分を渦粘性に繰り込む Subgrid Scale (SGS) モデルの構築が必要であるが，ユニバーサルな SGS モデルは存在せず，複雑な物理を包含する乱流場に対する SGS モデルの構築は一般に困難である。このため，数値粘性で SGS モデルを代用する陰的 LES が，その適用範囲の広さから実用計算で多用されている。しかし，衝撃波が発生する複雑な圧縮性乱流場に適した陰的 LES は未だ確立されていない。本論文は，圧縮性乱流場解析に供する陰的 LES コードの構築と検証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，重み付き非線形コンパクトスキーム(Weighted Compact Nonlinear Scheme; WCNS)を用いた陰的 LES コードを開発して一次元バーガーズ乱流を解いている。WCNS は単調性を有する高次精度スキームであることから，バーガーズ乱流の特徴である尖った波形を正確に捕捉しており，これによってバーガーズ乱流のエネルギースペクトラムに現れる慣性領域が格子幅で決まる最大波数域まで正確に再現できることを示している。また，バーガーズ乱流に対する直接解法の解や SGS モデルを用いる通常の LES による解との比較から，WCNS を用いる陰的 LES は，格子幅に依存することなくバーガーズ乱流の再現に必要な最小限の数値粘性を与えることが示されている。これは，圧縮性乱流場の陰的 LES を実現するために非常に重要な知見である。

第 3 章では，最初に WCNS を用いた陰的 LES コードを用いて二次元非圧縮性等方性乱流場を解き，直接解法の解や SGS モデル用いる通常の LES の解との比較から，エネルギースペクトラムに現れる慣性領域が格子幅で決まる最大波数域まで正確に再現できることを示している。次に，圧縮性流れに対する陰的 LES コードを用いて低マッハ数域の二次元圧縮性等方性乱流場を解き，得られたエネルギースペクトラムを比較することによって，圧縮性の場合でも慣性領域が正しく求められることを明らかにしている。これは，WCNS を用いた陰的 LES コードが圧縮性乱流場に適用できることを明らかにした有益な知見である。

第 4 章では，圧縮性乱流場に対する陰的 LES コードを用いて，後ろ向き段差を過ぎる三次元超音速乱流場の解析を行っている。流れ場中に生じる衝撃波を正しく捕らえながら，壁面近傍の境界層や再循環領域中に発達する縦渦群を捕捉しており，圧縮性乱流場の陰的 LES を実現している。計算結果は，後ろ向き段差における表面圧力分布に関する実験データを再現している。これは，WCNS を用いた陰的 LES が三次元圧縮性乱流場の解析に適用できることを示しており，複雑な物理を包含する圧縮性乱流場の解析手法の確立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，圧縮性乱流場に対する陰的 LES の開発と検証を行い，圧縮性乱流場の数値解析手法の基盤を構築したものであり，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。