Numerical and Experimental Study of Shock/Turbulent Flow Interaction(衝撃波と乱流の干渉に関する研究)

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論 文 内 容 要 旨

In this thesis, a numerical and experimental study has been conducted on the shock wave interaction with homogeneous, isotropic turbulence. A three-dimensional code has been developed to solve Reynolds-averaged Navier-Stokes equations with turbulence model. All the relevant turbulence parameters are resolved with turbulence model and the shock wave is resolved as a solution of Navier-Stokes equations with introducing the technique of shock capturing and HLL Reimann solver is used for shock capturing in the flow. The velocity fluctuations are measured at the period of expansion in the turbulent region due to incident shock wave movement and during compression by the reflected shock wave on turbulent field and it is observed that the longitudinal turbulent velocity fluctuations are enhanced both in the period of expansion and compression. The outcomes of shock/turbulence interaction depend on the shock wave strength, the flow velocity behind the shock wave and the longitudinal velocity difference across the shock wave. A numerical measurement is taken before and after the interaction of turbulent field with different strengths of shock wave. After the shock/turbulence interaction, the longitudinal turbulent velocity fluctuations are amplified and the amplification magnitude varies for the different strengths of shock wave. The amplification of longitudinal turbulence intensity in weak shock/turbulence interaction is higher value than in strong shock/turbulence interaction. Similarly after the shock/turbulence interaction, the turbulent kinetic energy (TKE) level is amplified and the amplification of TKE level in weak shock/turbulence interaction is higher value than in strong shock/turbulence interaction. The longitudinal velocity across the shock wave also effects on the amplification of longitudinal turbulence intensity and the amplification of TKE level. The longitudinal velocity across the shock wave increases due to partial reflection of the shock wave from the grid-typed shock reflector and it is observed that the amplification of longitudinal turbulence intensity and the amplification of TKE level become lower as increasing the longitudinal velocity across the shock wave. The dissipation rate of turbulent kinetic energy is observed in all the cases of shock/turbulence interaction and it is observed that the dissipation rate of turbulent kinetic energy is decreased after the shock/turbulence interaction. In the experimental works, the 1D hot wire anemometer is used to measure the turbulence intensity as well as the outcomes of shock wave interaction with turbulent field and it is observed that the turbulence intensity is amplified due to shock wave interaction with turbulence.

For the purpose of code validation test, the computations are conducted for the case of 2D nozzle flow and the numerical results are compared with that of experimental results. A good numerical simulation for nozzle flow depends on the throat area and the converging/diverging angle of the nozzle and the strength of the shock wave propagate through the throat of the nozzle. For small throat area of the nozzle, the flow separation will be high and blockage ratio will be low. In that case, it is necessary to select the shock wave strength comparatively high for good numerical simulations. So it is found that numerical results for higher shock Mach number have the good agreement with experimental results. Other flow parameters like fluid viscosity, Reynolds number also effect on the simulation results.

After the validation test of the Navier-Stokes equations, the extended three-dimensional Navier-Stokes equations with turbulence model are developed to solve almost all types of shock/turbulence interaction problems. Even though such type of computations is complex to get proper solution, but maximum simulated data agrees with the experimental results, performed by other researchers. In these computations, three-dimensional adaptive grids are used to get more accurate solution. Due to grid adaptation, the number of new cell, generated after refining operation, is twice the number of new cell, generated in two-dimensional adaptation and also adaptation is happened in the direction of the three Cartesian Coordinates. So the total number of cell difference between two subsequent refinement levels increases sharply, as a result, increases the computational time. The advantage of three-dimensional code is to solve all the turbulent parameters in the three-dimensional space system because the shock/turbulence interaction effect is one of the three-dimensional problems. The study of the grid convergence test has been performed successfully with different levels of grid refinement and also with different sizes of the grid. It is observed that all the simulation results are completely independent of the present grid system. The comparisons between the present simulation results and the NS results have been conducted successfully and it is observed that there have the good agreements between the present simulation results and the NS results.

The present computational results indicate that the outcomes of shock/turbulence interaction depend on the strength of the shock wave as well as the strength of turbulence. Experimentally and numerically many researchers got different values of the amplification of turbulence intensity for weak shock wave interaction with the turbulent flow. The amplification for higher Mach region is still questionable matters. The present computations indicate that the amplification of turbulent kinetic energy levels are higher value in interaction of comparatively weak shock with turbulent fields and decrease this value in interaction of strong shock with turbulent fields. After interaction, the dissipation rate of TKE decreases in all the cases of shock/turbulence interaction.

The interactions of shock wave with different strengths of turbulence are simulated and it is observed that the amplification of turbulence intensity and TKE level depend on turbulence strength and it is found that the amplification of turbulence intensity and TKE level vary in interaction of normal, reflected shock wave with different strengths of turbulent fields. The present interaction results provide the important information on strong shock wave interaction with different strengths of turbulent fields. All turbulent length scales decrease after interaction of strong shock wave with different turbulent fields and these results agree with other existing computational results.

The turbulent field interaction with different strengths of shock waves, reflected from shock reflector, gives different outcomes after interaction and it is observed that the amplifications of turbulent intensity are lower values in interaction of partial reflected shock wave with turbulent field as compare to the case of plane end wall reflection. Similarly the amplifications of turbulent kinetic energy level are lower values in interaction of partial reflected shock wave with turbulent fields as compare to the case of plane end wall reflection.

The shock wave reflection from different types of shock reflector has been investigated by means of Navier-stokes simulations with turbulence model. The results have been compared with the NS results. The simulation shows that the longitudinal velocity behind the reflected shock wave increases due to partial reflection from shock reflectors. The different strengths of the shock waves after reflection from shock reflectors enter in the similar turbulent region. The outcomes of shock/turbulence interaction strongly depend on the reflection techniques. In the case of full reflection, the temperature deviations in the downstream of the reflected shock wave is high as compare to the temperature deviations in the case of partial reflection. The amplification of dissipative length scale decreases after the shock/turbulence interaction and more decreasing values are observed for the reflection from the plane end wall. Similarly the amplification of velocity length scale also decreases and more decreasing values are observed for the reflection from the plane end wall. After measuring the dissipation rate of TKE, it is observed that the dissipation rate is decreased in interaction of shock wave with turbulent flow and the dissipation rate is decreased more in strong shock wave interaction with turbulent flow.

The accuracy of the experimental results on shock/turbulence interaction depends on the performance of the instruments and also depends on the sensitivity of the hot wire anemometer. The velocity fluctuations are amplified due to interaction of the reflected shock wave with the turbulent field and in this case, it is necessary to control the velocity fluctuations behind the transmitted shock wave by using different opening areas of the grid plate. Due to different types of grid plate, the strength of transmitted shock wave and the turbulence intensity change simultaneously. So the study on different turbulence grid plates will clarify the effect of turbulence strength on shock/turbulence interaction. Numerical simulations are also conducted on the experimental results and it is observed that there have the good agreements between the numerical results and experimental results.

論文審査結果の要旨

衝撃波と乱流との干渉現象は、流体力学あるいは衝撃波力学の研究課題であるばかりでなく、スクラムジェットエンジン燃焼室での混合あるいは可燃混合気中で爆燃波に駆動される衝撃波が爆轟波へ遷移する素過程の解明にも関連する。しかし、この素過程としての衝撃波管内で格子により形成された渦ないし乱流と衝撃波との干渉現象は、実験的にも解析的にも十分な解明はない。本論文は、壁面に発達する境界層の影響を無視できる程度に大きな断面の縦型衝撃波管に注目して、衝撃波と格子乱流との干渉過程を数値解析的ならびに実験的に解明した結果をとりまとめたもので、全編6章よりなる。

第1章は緒論である。

第2章では、ナビエ・ストークス方程式の数値解析法について述べ、計算結果を衝撃波管でのノズル実験の可視化結果と対比している。その結果を発展させて、正方格子多孔板を通過する衝撃波背後に形成される流れに及ぼす計算格子の影響を明らかにしている。

第3章では、正方格子多孔板を過ぎる衝撃波背後に形成される渦ないし乱流構造と固体壁から反射する衝撃波の相互作用、入射衝撃波マッハ数、乱流運動エネルギー、乱流強度を数値的に明らかにしている。

第4章では、第3章の結果をさらに発展させて、正方格子多孔板の背後に第二の正方格子多孔板を置き、その開口比を変え反射衝撃波の強さを制御し、最初の格子板でできた乱流と干渉させて、衝撃波強さの効果、乱流運動エネルギー、乱流強度の変化を数値的に明らかにしている。多孔板を導入して反射衝撃波の強さを比較的広い範囲で変化させる着想は独創的で、得られた結果は重要な知見である。

第5章では、300 mm x 300 mm 断面の縦型衝撃波管に正方格子多孔板を取りつけて、壁面静圧測定と熱線風速計での乱れ計測で衝撃波前後の乱流強度変化および圧力変動を求め、得られた結果を数値解と比較し比較的良い一致を得ている。衝撃波干渉によって乱流強度の増加を定量的に明らかにしている。これは評価に値する結果である。

第6章は結論である。

以上要するに本論文は、衝撃波と乱流の干渉を衝撃波管内流れに着目して、数値解析的にまた実験的に解明したもので、航空宇宙工学および衝撃波工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。