Numerical Simulation of Non-Steady Supersonic Double Ramp Flow by URANS Approach

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Abstract. The supersonic M=2.5 double ramp flow simulations performed on a basis of URANS approach for different distances between the ramp angles have been carried out. Two advanced turbulence models have been examined and the results obtained by the simulations are compared. A validation of the computational results on the experimental mean wall pressure distributions has been carried out. An ability of URANS-based approaches to simulate unsteady effects is evaluated.

Key words: supersonic turbulent flow, shock waves, URANS, double ramp.

1. Introduction

Shock wave / boundary layer interaction (SWBLI) including flow separation remains an urgent topic for investigations though many studies on this problem have been performed since 1950th. From the numerical point of view even prediction of the mean flow parameters keeps somewhat complex task. Some progress in this direction has been achieved with the aid of modern CFD approaches such as LES and DNS [1, 2]. However, due to high computational time costs these methods are believed to be unsuitable for industrial applications in their wide variety of geometrical and flow parameters. As an alternative, URANS-based models can be used. It was observed however, that URANS prediction in many cases does not agree with measurements. A possible reason is an unsteadiness of the SWBLI [3]. The unsteadiness is important to investigate in order to evaluate aero and heat loadings which appear during these kinds of interactions. They play an important role in many applications, such as high-speed vehicles, scramjet inlets, missiles, etc. The origins of this non-stationary behavior have not been cleared up yet, though different mechanisms of the phenomenon have been proposed [4—6].

2. Problem Statement and Methods of Investigation

A supersonic flow in vicinity of a double ramp configuration with ramp angles of $\alpha_1 = 11^\circ$ and $\alpha_2 = 9^\circ$ is investigated. The distance between the two kinks is varied from 0 to 39 mm. In the current paper, a dimensionless distance d is used, normalized by the incoming boundary layer thickness $\delta = 5.15$ mm. The calculations were conducted jointly with experimental research by Gaisbauer et al. [7] for the three sets of flow parameters. The results for the two flow sets have been presented earlier in [8], namely, of Mach number 2.54 and unit Reynolds number $12.7 \cdot 10^6$ 1/m, and of Mach number 2.995 and unit Reynolds number $7.5 \cdot 10^6$. In the present paper, the results for the following freestream parameters are presented: Mach number M=2.513, unit Reynolds number $\mathrm{Re} = 9.82 \cdot 10^6$ 1/m, total pressure $P_0 = 93400$ Pa, total temperature $\mathbf{T}_0 = 283$ K.

The numerical investigation is carried out by an original 2D URANS-based code, developed at ITAM SB RAS, Novosibirsk, Russia [9]. The Favre-averaged compressible Navier-Stokes equations for ideal gas are used. The $k-\omega$ Wilcox model [10] and SST model of Menter [11] for closure are implemented. The details of the numerical technique can be found in [8, 9]. The used regular grid has a toward-the-wall refinement and typically consists of 200 nodes in y-direction and 300 nodes in x-direction, unless otherwise mentioned.

3. Results and Discussion

3.1. WALL PRESSURE DISTRIBUTIONS

Wall pressure distributions for three cases of the ramp distances obtained by two turbulence models are presented in Figure 1. The first kink locates at $x = 0$. The considered distances d are shown in Figure. The dashed lines correspond to the $k-\omega$ model simulations and the solid lines show the SST model results. The skin friction distributions are presented in Figure 2 with the same notations.

Depending on d, three flow regimes were observed in the computations similar to those described in [8]. The first one is a coupled regime where the separation zones induced by the two shocks are combined in one large separation. The second regime is a transitional one with a short detached zone at the first angle and a zero skin friction coefficient area downstream. The third regime results in two spaced shocks, with a short separation in the vicinity of the first kink and an attached flow at the second kink.

A significant disagreement on pressure and skin friction distributions obtained by two different turbulence models is observed for the small distances between the kinks: d=1.83 and d=2.13. In these cases SST model predicts a big separation which covers both compression corners. It means that both flows belong to the first regime described above. It can be seen that the separation zone sizes are significantly overpredicted. While the results obtained by the $k-\omega$ model exhibit the second regime for d=1.83 and the third regime for d=2.13 that agrees with the experimental data. In a case of a longer distance d=5.3 when only small separation near the first kink takes place, the results of the both models differ slightly, and fit well the experimental wall pressure distributions.

The difference in the turbulence models' prediction can be connected with a special treatment included in SST model to simulate flows with adverse pressure gradients that prevents separation damping. It is also known that the turbulent viscosity level predicted by $k-\omega$ model is influenced by a freestream value of the specific turbulence dissipation rate ω_∞, which was taken as $1.66 \cdot 10^5$ 1/s in the present computations.

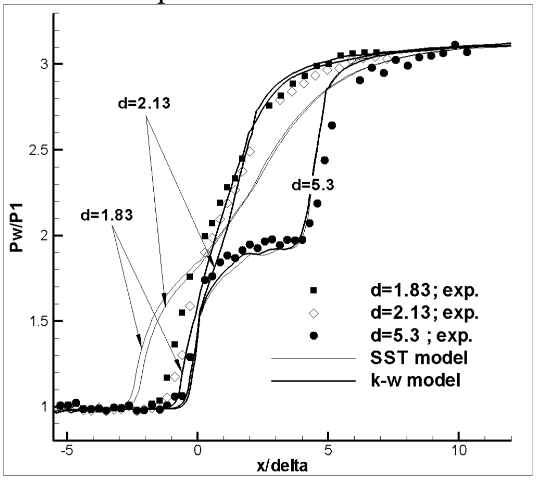

Figure 1. Wall pressure distributions for different distances between the kinks

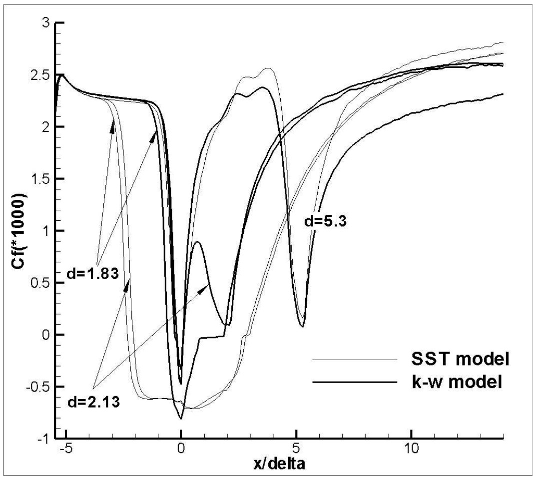

Figure 2. Skin friction distributions for different distances between the kinks

3.2. FLOW UNSTEADINESS

As it is known [12], two types of SWBLI unsteadiness can be distinguished during the interaction depending on their frequency range. Shock experiences both large-scale, low amplitude motion connected with pulsations of the separation zone, and small-scale, high frequency motions, caused by turbulent fluctuations passing through the interaction. Results of the flow parameters' prediction depend essentially on reproduction of these effects.

It was demonstrated in Conclaves et al. [13] that large scale shock movements can be caught by URANS-based methods. However, the calculations carried out in the present paper have shown no unsteady shock behaviour. It can be explained by a small scale of the oscillations and, on the other hand, by a high numerical viscosity of an implemented numerical scheme. Further investigations are necessary in order to check thoroughly the approach abilities.

In the present computations only small oscillations of the flow parameters behind the shocks have been observed. In order to investigate the source of these oscillations, a numerical simulation with a fine grid of 500 nodes in x-direction and 300 nodes in y-direction for the case of d=3.87 has been performed. The density contours are presented in Figure 3. The density range varies from 0.152 to 0.344 kg/m^3 by 353 contour lines. In Figure 3 two spaced shock waves (*1* and *2*) arising from the ramp kinks and the resulting shock wave *3* can clearly be seen. Inviscid shock wave interactions and the secondary wave formation have been considered in particular in [14] with several examples. Accordingly to the classification in [15], the VI type interaction of shock waves takes place. In order for the flow to attain the appropriate entropy level, an additional contact line *4* and a secondary expansion wave *5* arise. For the same reason, small pressure perturbations are also generated behind the first shock wave and more evident ones *6* after the second shock. Observations have shown that they are non-stationary and change their locations with time.

From the calculations on subsequently refined meshes the pressure distributions at the edge of the boundary layer for different grid steps were obtained. They are presented in Figure 4. The perturbation wave length does not change noticeably with the grid refining and it can be supposed that these flow oscillations are not a numerical effect. Numerical method modification together with further grid refinement and Fourier analysis of the pressure fluctuations are needed to get clear understanding of the unsteadiness origins.

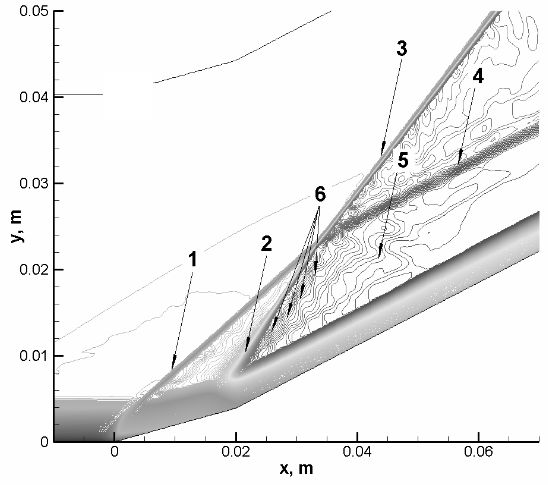

Figure 3. Density contours for d=3.87

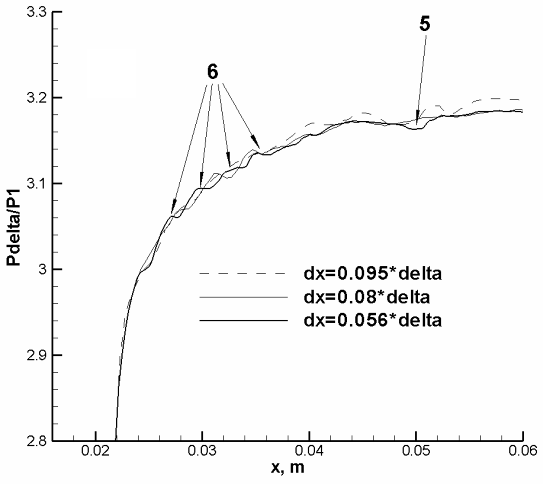

Figure 4. Pressure distributions on the boundary layer edge for different numerical grids for d=3.87

4. Conclusions

The URANS-based simulation of the double ramp supersonic configuration at unit Reynolds number $9.8 \cdot 10^6$ 1/m has been carried out. An ability of the averaged Navier-Stokes equations to predict flow behaviour in the vicinity of such geometry is found out to be reasonable. Results of two different turbulence models were compared on a base of the experimental wall pressure distributions. Small pressure and density perturbations behind the shock fronts have been discovered and an assumption concerning their influence on a shock position has been made. Future work will be directed toward experimental and numerical investigations of non-stationary effects (with the aid of the URANS algorithm), since the non-steadiness can essentially influence the flow parameters.

Acknowledgements

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