Computational Simulation of Vortex Generator Effects on Transonic Shock/Boundary-Layer Interaction

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Abstract

THE present work describes a theoretical simulation of the effects of a vortex generator row ahead of a shock/boundary-layer interaction zone. The row is represented by parameters characterizing the Law of the Wall/Law of the Wake structure of the turbulent boundary layer. This model is then integrated into a previously developed two-dimensional computational code that utilizes an appropriate triple-deck theory of a nonseparating shock/boundary-layer interaction. The results imply that the shape factor reduction effect associated with a vortex generator can have powerful, favorable effects on the local and overall interactive properties, but can also promote earlier incipient separation in the immediate vicinity of the shock foot.

Contents

The influence of shock/boundary-layer interaction on a supercritical wing can extend significantly downstream within the boundary layer and thus adversely affect global aerodynamic properties. This negative influence may be reduced by means of the boundary-layer control device known as the vortex generator, which delays separation by promoting mixing between the freestream and the boundary layer. The present paper describes a method that computationally simulates the gross spanwise-averaged two-dimensional effects of a vortex generator row located ahead of an unseparated shock/boundary-layer interaction zone such as that found on a supercritical wing (see Fig. 1). The model of this situation is based on fundamental Law of the Wall/Law of the Wake relations for the incoming turbulent boundary layer, combined with a triple-deck theory of the subsequent interaction zone.

Triple-Deck Structure

In the practical Reynolds number range of interest here ($10^5 \leq Re_\delta \leq 10^{10}$), the shock/boundary-layer interaction region is described by a nonasymptotic triple-deck theory[1] for nonseparating two-dimensional flow that has been extensively validated by experiment.[2] This approach includes three aspects of particular importance to such Reynolds numbers: 1) an account of the lateral pressure and streamline slope variations across the middle deck, 2) accurate treatment of the interactive changes in the eddy viscosity within the inner deck adjacent to the wall, and 3) inclusion of the powerful influence of the incoming boundary-layer shape factor on the interactive disturbance field in both of these decks. This later aspect is accommodated by employing for the incoming turbulent boundary-layer velocity profile a very general nonequilibrium Law of the Wall/Law of the Wake model due to Walz,[3] combined with an adiabatic wall reference temperature correction for compressibility and the Crocco energy equation integral for the temperature distribution.

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Simulated Vortex Generator Effects

The gross spanwise-averaged effects of the vortex generator (VG) row are simulated via their influence on the boundary-layer properties that are involved in the Law of the Wall/Law of the Wake model of a turbulent boundary layer. From the studies by Schubauer and Spangenberg,[4] it is known that these effects primarily consist of an increase in momentum thickness due to the drag of the VG device, followed by a decrease in both the boundary-layer shape factor and displacement thickness plus an increase in skin friction due to the enhanced fluid entrainment. In effect, the vortex generator significantly reduces the outer Law of the Wake part of the boundary layer, while retaining the inner Law of the Wall structure.

Along with an assumed knowledge of the undisturbed boundary-layer properties at station 3 (Fig. 1), the VG row is characterized by two parameters: 1) the momentum thickness increase fraction $(\Delta\theta^*/\theta^*)_D$ due to its drag, and 2) the fractional shape factor decrement $\Delta Hi/Hi$ associated with the mixing effect (which includes the influence of detailed vane shape). Then from the classical Law of the Wall/Wake relationships governing the momentum thickness, displacement thickness and skin friction plus one accurate simplifying assumption, it is possible to derive equations governing the VG-modified pre-interaction boundary-layer properties of skin friction, displacement thickness Reynolds number, and wake function (see the cited source paper for details). This method was incorporated into the program that implements the aforementioned shock/boundary-layer interaction theory and a parametric study then made of the relative effects of different types of vortex generators as characterized by $\Delta Hi/Hi$ and $(\Delta\theta^*/\theta^*)_D$, where values of 10% represent a fairly strong VG effect.

It is emphasized that the foregoing averaged two-dimensional simulation of the vortex generator row ahead of the interaction is intended only as a gross account of the main qualitative effects: it is understood that it does not give an account of the details of the turbulent entrainment process in-

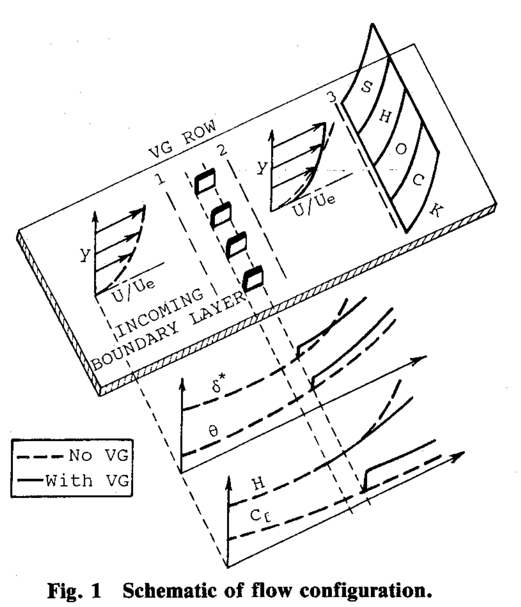

Fig. 1 Schematic of flow configuration.

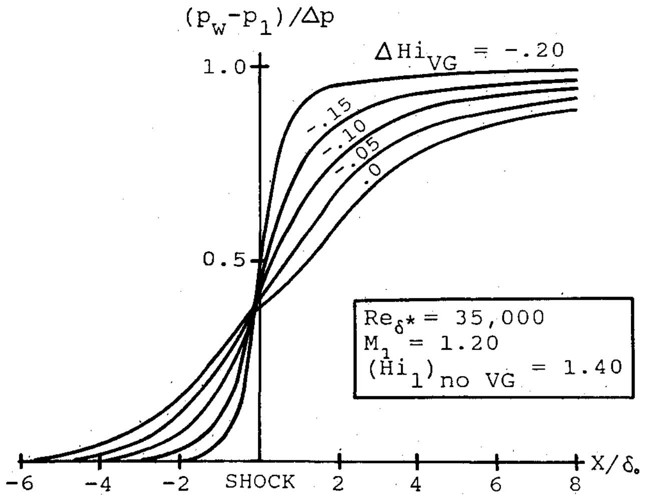

Fig. 2 Typical effect of VG-induced shape factor reduction on interactive pressure distribution.

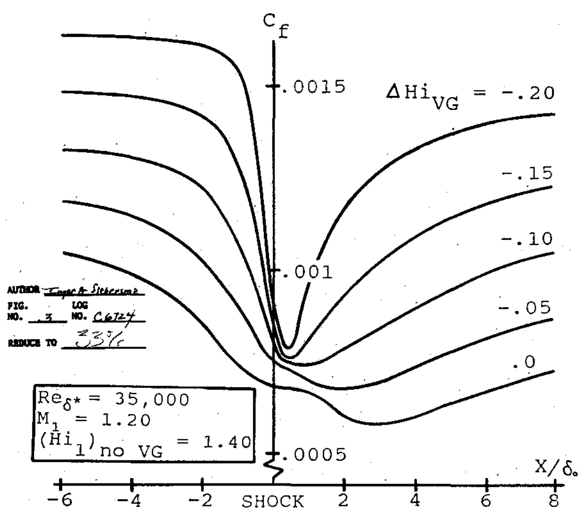

Fig. 3 Effect of VG on interactive skin-fraction distribution.

volved nor of the subtler aspects of the detailed vane geometry.

Parametric Study Results

Since it is the most significant VG effect, consider first the role of the shape factor for a typical nonseparating Mach 1.20 interaction with an incoming incompressible shape factor value (without VG) of 1.40. Figure 2 shows the predicted influence of the degree of VG-induced shape factor reduction on the wall pressure field across the interaction zone at a Reynolds number of $Re_\delta{}^* = 35{,}000$. It can be seen that this decrease in shape factor significantly reduces the streamwise extent of the pressure rise and, hence, increases the pressure gradient across the interaction zone; the corresponding interaction displacement thickness growth was found to be significantly decreased. The attendant influence on the local interaction skin-friction coefficient distribution is shown in Fig. 3, where two conflicting effects can be seen. The larger pressure gradient caused by a lower shape factor results in a more rapid decrease in skin friction and lower minimum C_f values in the shock foot region; however, this is offset by the higher initial upstream skin friction, which is then partially recovered downstream of the shock. Therefore, a vortex generator row can be expected to promote earlier incipient separation within the interaction, while increasing the C_f (and, hence, the separation resistance) of the postinteraction momentum thickness θ^*_{pi}; for example, a 17% reduction in θ^*_{pi} was found for a VG having a 10% reduction in H_i. With such a reduced θ^*_{pi}, the subsequent turbulent boundary layer would be able to negotiate either a stronger adverse pressure gradient over a given distance or a given pressure gradient over a longer distance without separation. This was found to hold true over a range of shock strengths and Reynolds numbers.

Further study was also carried out as to the influence of both Mach number (shock strength) and Reynolds number on the interactive VG effect. The former indicated that the effect increases moderately with the overall strength of the interaction. The latter role of Reynolds number ("scale" effect) was seen to be that the VG effect reduces the sensitivity of the overall interactive pressure gradient and displacement thickness growth to changes in $Re_\delta{}^*$.

Conclusions

The present simulation study suggests that the shape factor-reduction effect associated with the VG row can have powerful favorable effects on a subsequent shock/boundary-layer interaction, but can also promote earlier incipient separation in the immediate vicinity of the shock foot. These predictions, however, still await experimental confirmation and, as such, are to be considered exploratory and preliminary.

References

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