Effect of Vectored Suction on a Shock-Induced Separation

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Nomenclature

e = specific energy
E,F = flux vectors
M = Mach number
q = total velocity, $\sqrt{u^2+v^2}$
t = time
U = independent variable
u,v = velocity components
x,y = coordinates in the physical plane
X_{SHK} = shock impingement point, 4.953×10^{-2} m
ρ = density
ξ,η = coordinates in the computational plane
θ_{SHK} = incident shock angle
ϕ = suction angle

Subscripts

w = surface condition
∞ = freestream condition

Introduction

THE performance criteria associated with aircraft, satellite launch vehicles, etc., strongly depend on the thickening boundary layer and the subsequent external shock-induced separation, which explicitly influences the point of transition in the viscous layer from laminar to turbulent, resulting in an increase in drag. One of the powerful tools for controlling this undesirable feature is suction through solid surfaces. Tassa and Sankar[1] have shown that for a two-dimensional flow, even a modest amount of normal suction, about 0.3% of the freestream velocity, substantially reduces the boundary-layer thickness in the separation region. For a strong shock causing separation, the pressure diffusion in the impingement region could be curtailed effectively if the decelerating fluid particles are removed before they reach the interaction zone. This procedure can be further reinforced if instead of a normal suction, a vectored suction is used. This aspect of the procedure is closely examined in the present numerical study by solving compressible Navier-Stokes equations.

Analysis

The unsteady, compressible Navier-Stokes equations in the transformed coordinates are written in the following form:

$$\frac{\partial U}{\partial t}+\xi_x\cdot\frac{\partial E}{\partial \xi}+\xi_y\cdot\frac{\partial F}{\partial \xi}+\eta_x\cdot\frac{\partial E}{\partial \eta}+\eta_y\cdot\frac{\partial F}{\partial \eta}=0$$

where $U=[\rho, \rho u, \rho v, \rho e]^T$ and E and F are flux vectors. The physical space x, y is transformed into a unit square computational domain using a nonsingular Jacobian and a homotopy scheme. The governing equations are solved by the well-established MacCormack's explicit finite-difference scheme[2,3] after introducing perfect gas law and Sutherland's formula to close the system.

Received Jan. 30, 1986.

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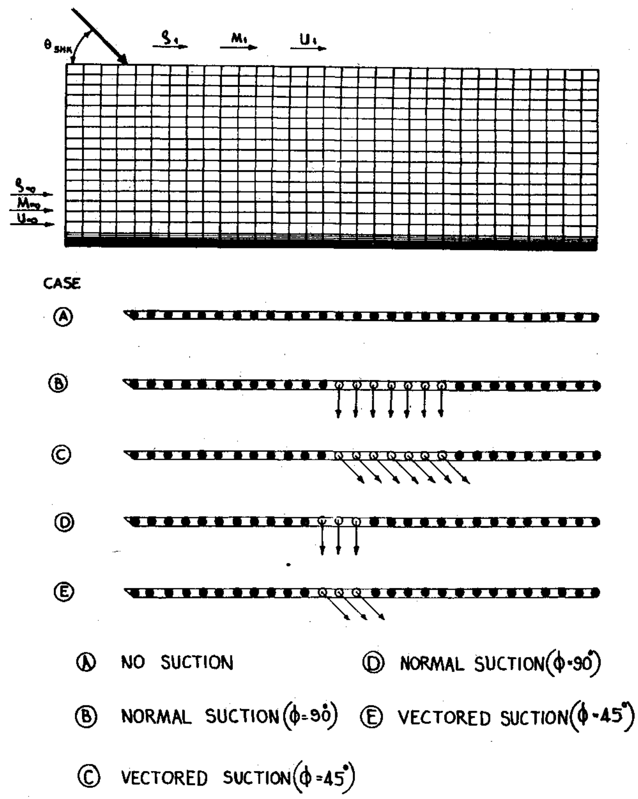

Fig. 1 Suction locations and angles.

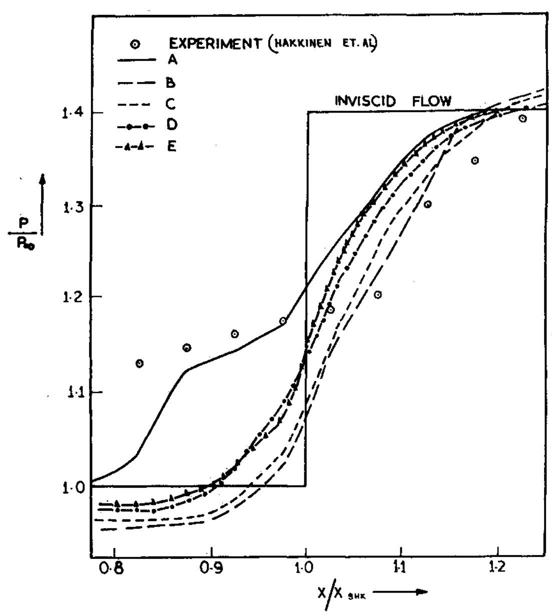

Fig. 2 Surface pressure distribution.

The physical space (Fig. 1) is discretized into 32 uniformly spaced points in the x direction and 29 exponentially stretched and 16 uniformly spaced points in the y direction. The minimum mesh size in the normal direction was 0.331×10^{-4} m. The initial and boundary conditions for this grid system are straightforward except at the solid surface locations where suction is applied. At those locations, for the constant suction Mach number M_w of 0.006 ($v_w/q_\infty=-0.003$)[1], for normal suction $u_w/q_\infty=0.00$, $v_w/q_\infty=-0.003$, and for vectored suction $\phi=45$ deg, $u_w/q_\infty=0.00212$, and $v_w/q_\infty=-0.00212$ are specified. These uniform suction rates are so small that the no-slip condition at the wall can be safely retained.

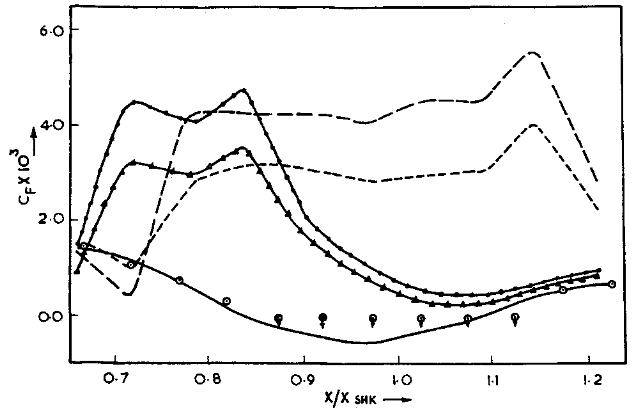

Fig. 3 Skin-friction distribution.

Results

The typical case considered is for a freestream Mach number of 2.0, a Reynolds number of 0.296×10^6 based on the distance X_{SHK} from the leading edge to the shock impingement point, and an incident shock angle of 32.585 deg.[4] For this set of data, the shock is strong enough (pressure ratio = 1.4) to trigger separation. The computation was done for five cases: 1) no suction along the wall, 2) normal suction, $\phi = 90$ deg at the location from $X/X_{SHK} =$ 0.7817 to 1.1569, 3) vectored suction, $\phi = 45$ deg at the locations as in case 2, 4) normal suction from $X/X_{SHK} = 0.7192$ to 0.8442, and 5) vectored suction at the same locations as in case 4.

The computed surface pressure distribution in the interaction region is presented in Fig. 2. For the vectored upstream suction case 5, the pressure jump is closes to the inviscid flow conditions case and reaches its postshock value quite smoothly. It is interesting to note that the pressure rise is steeper than that corresponding to normal suction. Though the pressure plateau indicating separation has vanished for all the examples in which suction is considered, the upstream vectored suction has a minimum effect in the downstream direction (Fig. 3).

This study indicates that the upstream vectored suction not only eliminates separation but that its influence in the neighborhood is limited. If the prior knowledge of separation bubble location is not available or some minor changes in the input data are required, a judicious choice of upstream vectored suction can control the flow effectively. However, a detailed assessment regarding the locations, rates, and angles, for such suction should be carried out to optimize its fruitful usage.

References

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Rapid Computation of Unsteady Transonic Cascade Flows

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Introduction

REFERENCE 1 describes a method for computing the unsteady flow through a cascade for an interblade phase angle using only one set of computational data. This computational data is calculated for one blade moving with the other blades held stationary. Further simplification is possible because only the indicial response of the cascade needs to be calculated; from this result the flow for any time-dependent motion can be constructed by superposition. For subsonic or supersonic flows, the indicial method is described by Lomax,[2] the method was developed for transonic flows by Ballhaus and Goorjian[3] and Nixon.[4] Nixon shows that unsteady pressure distributions can be computed for transonic flows and that, to a first-order approximation in shock motion, the lift and pitching moments are linear functions of amplitude. Because of the need to compute only one transonic flow solution in order to obtain a result for any interblade phase angle and motion, the method developed in Ref. 1 is very computationally efficient.

The main difficulty in constructing the indicial solution for the cascade is that a reasonable number of fixed blades must be represented in the calculation. The definition of reasonable will be discussed later. In the first attempt[5] to compute examples using the method of Ref. 1, seven blades were used in the computation, and the results for a flat plate cascade in subsonic flow did not agree well with the results of Verdon and Casper.[6] The most obvious difference was the absence of resonance in the indicial theory result. It was speculated that the disagreement resulted from insufficient blades in the cascade. It is obvious that if a large number of blades are required in the cascade, the computational efficiency of the method is greatly reduced, since the indicial calculation could require computer resources equivalent to that used to calculate cascade flows for a variety of interblade phase angles. In this Note a method of including a large number of blades in the calculation without incurring a heavy computational requirement is described. Results that are a considerable improvement on those described in Ref. 5 are given. The analysis contained herein is for an unstaggered cascade.

Analysis

Although the indicial theory described in Ref. 4 can give pressure distributions, only lift and pitching moments are considered here for reasons of clarity in presentation. The gap/chord ratio is denoted by h and the freestream Mach number by M_∞.

The lift given by the theory in Ref. 1 is

$$C_L(t) = \sum_{n=-\infty}^{\infty} C_{L_n}(t - n\sigma) \tag{1}$$

Received July 24, 1986.

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