AIAA 80-0062R

Flow Oscillations of Spike-Tipped Bodies

J. S. Shang* and W. L. Hankey†
Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio
and
R. E. Smith‡
NASA Langley Research Center, Hampton, Va.

Abstract

THE oscillating flowfield around a spike-tipped body was simulated by the numerical solution of the three-dimensional Navier-Stokes equations at a Mach number of 3.0 and a nominal Reynolds number of 7.87×10^6/m. Computations were performed using a vectorized three-dimensional Navier-Stokes program on the STAR 100 computer. Numerical solutions confirmed the experimental result that the self-sustained oscillation occurs within a limited range of the protruded spike length to shoulder height ratio. The numerical result predicted correctly the discrete frequency range as well as the rms pressure intensity. The detailed flow structure is also presented and discussed.

Contents

Introduction

The occurrence of "buzz" on spike-tipped configurations and re-entry nose tips has been studied for several years. These self-sustained oscillations have been observed for a wide variety of shear layer impingement configurations.[1,2] The highly organized oscillations of an impinging flow are sustained by feedback or upstream pressure propagation through the subsonic separated region to the shear layer origin and by a selective disturbance amplification of the fluctuations in the shear layer between separation and impingement.

For the oscillating flowfield around a spike-tipped configuration, the experimental data[3] reveals several unique features which require additional elaboration (see Fig. 1). First, the oscillatory motion occurs only for a certain range of the protruded spike length at a fixed value of the spike and afterbody diameter. The measured rms value of pulsating pressure nearly vanishes at a spike length of about 12.7 mm. However, at the other extreme, increasing spike length, the rms pressure value drops rapidly after reaching its maximum.

Several numerical solutions[4-6] using the Navier-Stokes equations have been obtained for flows over indented nose tips. Widhopf et al.[4] have indicated that the oscillatory frequency does not show a strong variation with the Reynolds number. In addition, they suggested that the essentially viscous nature of the problem is the no-slip condition at the surface which generates inflection points in velocity profiles. Their solutions were obtained for relatively low Reynolds numbers, however (in the order of magnitude of a few hundred based on the nose radius).

Presented as Paper 80-0062 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16, 1980; submitted Feb. 7, 1980; synoptic received March 2, 1981. This paper is declared a work of the U.S. Government and therefore is in the public domain. Full paper available from AIAA Library, 555 W. 57th Street, New York, N.Y. 10019. Price: Microfiche, $3.00; hard copy, $7.00. **Remittance must accompany order.**

*Aerospace Engineer. Associate Fellow AIAA.
†Senior Scientist. Associate Fellow AIAA.
‡Mathematician. Member AIAA.

The basic configuration of the present investigation consists of hemispherical nose cylinder connected to a truncated conical afterbody. The spike has a diameter of 12.7 mm. The diameter of the truncated conical afterbody at the junction is 50.8 mm and the cone half angle is about 9 deg. The connections between the spike, the truncated forward-facing surface, and the afterbody are rounded off with small radii of about 3 mm. In order to achieve a satisfactory computational mesh, the coordinates are first transformed from the Cartesian frame into a cylindrical polar coordinate system and then transformed again into body oriented coordinates (ξ, η, ζ) by means of a homotopy scheme.[7,8]

The system of equations is solved by a two-step predictor and corrector scheme originated by MacCormack.[9] For the present effort, the required numerical resolution in time usually is more stringent than the allowable time step from the stability consideration of the finite-difference approximation. Therefore, the rather restrictive allowable time step does not constitute a detriment to the efficiency of data processing.

The numerical evaluations were performed on the STAR 100 computer with the vectorized code of Smith and Pitts.[10] In order to eliminate excessive page faults and effectively use the available primary memory, the 32 bits arithmetic option (SL1) was adopted. The use of SL1 language not only reduced the core memory by a factor of two but also sped up the data processing rate from 1.50×10^{-4} to 6.0×10^{-5} s.[10,11] Most significantly, the numerical results between 64 and 32 bit arithmetics are well within the acccuracy requirement for engineering applications.

Discussion of Results

One of the major objectives of the present analysis is to verify that the self-sustained oscillatory flow is maintained by an instability of a free shear layer and the selectively amplified disturbance is then fed back through a reflecting pressure wave system. In the absence of either of these mechanisms, the oscillation eventually ceases.

In Fig. 1, the time history of pressure evaluated at the shoulder for both the long (38.1 mm) and short (12.7 mm) spike-tipped configurations is shown. For the longer spike-

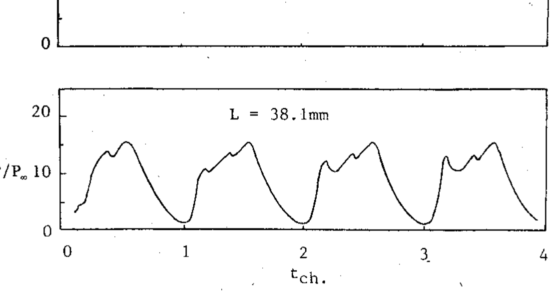

Fig. 1 Pressure histogram of spike-tipped bodies.

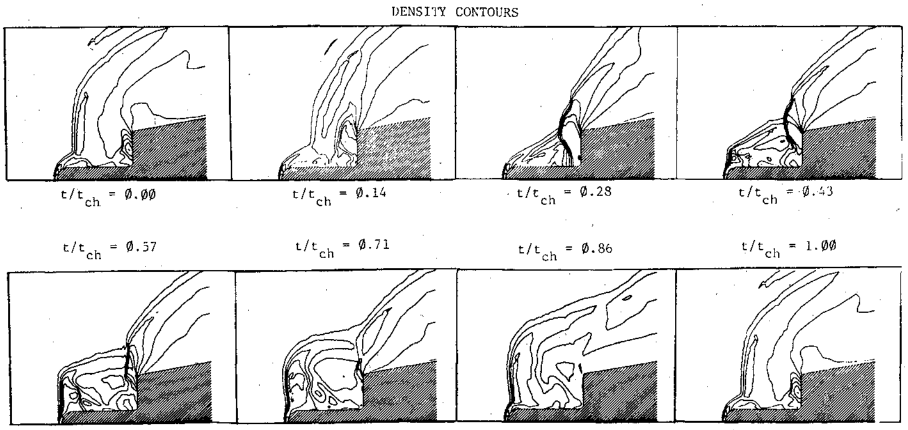

Fig. 2 Sequential density contours during one fundamental period.

tipped body, one observes the periodic variation emerges roughly about 0.0020 s elapsed (2000 time steps). The oscillatory behavior persisted over four periods and maintained its amplitude and wave form: no dramatic damping or decaying is recognized. The self-sustained oscillation is evident and the amplitude of pulsation is about 17 times the freestream pressure value. On the other hand the flow over the shorter spike-tipped body after the transient phenomenon decays the pressure is relatively steady compared to longer tipped configuration. This observation is in perfect accord with experimental observation.[3] The comparison between the spectral graph and the result of spectral analysis of the oscillating pressure distribution shows that the first four modes of discrete frequency are predicted within 7% of the experimental data.

A sequence of density contours is presented in Fig. 2. The time frames describe one principle period. The bow shock wave induced by the hemispherical tip is obvious. The disturbance propagates downstream toward the afterbody and amplifies in magnitude. After the oscillatory shear layer impingement, the reflected pressure wave is propagated upstream through the subsonic separated region to reinforce the oscillatory phenomenon by reintroducing a disturbance into the free shear layer. From the static display of the sequential density contours, one observes only the steady shock-wave formation at the nose tip and the pulsating shock in the shoulder region due to impingement. The entire process then repeats itself. Unfortunately, the upstream disturbance propagation can only be demonstrated by the dynamical display of the temporal events (computer movie).

Conclusion

The self-sustained oscillating flowfield around spike-tipped configurations were successfully simulated by numerical solutions of the time-dependent Navier-Stokes equations. The numerical solution predicts accurately the frequency and amplitude of the fundamental frequency and commensurable higher modes of oscillation observed in experiments. The numerical solutions also demonstrate that the self-sustained oscillatory motion is maintained by the selective amplification of disturbances in the shear layer as predicted by hydrodynamic stability theory. The feedback mechanism of an upstream propagating pressure wave through the subsonic separated layer that reintroduces a disturbance into the initial shear layer completely closes the chain of events. The present analysis indicates that numerical solutions are useful for investigating the stability of viscous flows.

Acknowledgments

The able assistance in data processing by Joan I. Pitts and Barbara L. Weigel of NASA Langley Research Center is acknowledged. The authors also are grateful to the Theoretical Aerodynamics Branch for the use of the STAR 100 computer at NASA Langley Research Center.

References

[1] Rockwell, D. and Nandascher, E., "Self-Sustained Oscillations of Impinging Free Shear Layers," *Annual Review of Fluid Mechanics*, Vol. 11, Annual Review, Inc., Palo Alto, Calif., 1979, pp. 67-94.

[2] Hankey, W. L. and Shang, J. S., "The Numerical Solution of Pressure Oscillations in an Open Cavity," AIAA Paper 79-0136, Jan. 1979.

[3] Harney, D. J., "Oscillating Shocks on Spiked Nose Tips at Mach 3," AFFDL-TM-79-9-FX, May 1979.

[4] Widhopf, G. F. and Victoria, K. J., "Numerical Solution of the Unsteady Navier-Stokes Equations for the Oscillatory Flow over a Concave Body," *Lecture Notes in Physics*, No. 35, Springer-Verlag, New York, 1974, pp. 431-444.

[5] Rakich, J. V., Vigneron, Y. E., and Tannehill, J. C., "Navier-Stokes Calculations for Laminar and Turbulent Supersonic Flow over Indented Nosetips," AIAA Paper 78-260, Jan. 1978.

[6] Kutler, P., Chakravarthy, S. R., and Lombard, C. K., "Supersonic Flow Over Ablated Nosetips Using Implicit Numerical Procedure," AIAA Paper 78-213, Jan. 1978.

[7] Eiseman, P. E., "A Coordinate System for a Viscous Transonic Cascade Analysis," *Journal of Computational Physics*, March 1978, pp. 307-338.

[8] Smith, R. E. and Weigel, B. L., "Analytic and Approximate Boundary Fitted Coordinate Systems for Fluid Flow Simulation," AIAA Paper 80-0192, Jan. 1980.

[9] MacCormack, R. W., "Numerical Solutions of the Interactions of a Shock Wave with Laminar Boundary Layer," *Lecture Notes in Physics*, Vol. 8, Springer-Verlag, New York, 1971, p. 151.

[10] Smith, R. E. and Pitts, J. J., "The Solution of the Three-Dimensional Compressible Navier-Stokes Equations on a Vector Computer," Paper presented at Third IMACS International Symposium on Computer Methods for Partial Differential Equations, Lehigh University, Pa., June 1979.

[11] Shang, J. S., Buning, P. G., Hankey, W. L., and Wirth, M. C., "The Performance of a Vectorized 3-D Navier-Stokes Code on the CRAY-1 Computer," *Proceedings of AIAA Computational Fluid Dynamics Conference*, July 1979, AIAA, New York, pp. 27-35.