supersonic pocket on the rotor blade surface, the initial separation of the acoustic wave from the aerodynamic field, and the propagation of the acoustic wave to the farfield. It is currently impossible to obtain such detailed information from experiments.

Conclusions

This study demonstrates the capabilities of a free-wake Euler and Navier-Stokes CFD methodology, called TURNS, in calculating helicopter rotor aerodynamic flowfields, including the acoustics (high-speed impulsive noise), in both hover and forward flight. The aerodynamics and acoustics information can be obtained in one single calculation. Agreement with experiments is very encouraging, demonstrating the ability of the solution scheme to capture the flowfield and acoustic details that are hard to obtain from experiments.

Acknowledgments

The authors would like to thank W. J. McCroskey for his encouragement and continued interest. The first author would like to acknowledge the research support from the U. S. Army Research Office under Contract DAAL03-90-C-0013.

References

[1]McCroskey, W. J., "Special Opportunities in Helicopter Aerodynamics," *Recent Advances in Aerodynamics,* edited by A. Krothapalli and C. A. Smith, Springer-Verlag, New York, 1986, pp. 721–752.

[2]Schmitz, F. H., and Yu, Y. H., "Helicopter Impulsive Noise: Theoretical and Experimental Status," *Recent Advances in Aeroacoustics,* edited by A. Krothapalli and C. A. Smith, Springer-Verlag, New York, 1986, pp. 149–243.

[3]Srinivasan, G. R., and Baeder, J. D., "Recent Advances in Euler and Navier-Stokes Methods for Calculating Helicopter Rotor Aerodynamics and Acoustics," *Proceedings of the Fourth International Symposium on Computational Fluid Dynamics* (Davis, CA), Sept. 1991, pp. 1095–1100.

[4]Baeder, J. D., "Euler Solutions to Nonlinear Acoustics of Non-Lifting Rotor Blades in Forward Flight," paper presented at the American Helicopter Society–Royal Aeronautical Society International Technical Specialists Meeting on Rotorcraft Acoustics and Rotor Fluid Dynamics (Philadelphia, PA), Oct. 1991.

[5]Srinivasan, G. R., Baeder, J. D., Obayashi, S., and McCroskey, W. J., "Flowfield of a Lifting Rotor in Hover—A Navier-Stokes Simulation," *AIAA Journal,* Vol. 30, No. 10, 1992, pp. 2371–2378.

[6]Baldwin, B. S., and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flow," AIAA Paper 78-0257, Jan. 1978.

[7]Caradonna, F. X., and Tung, C., "Experimental and Analytical Studies of a Model Helicopter Rotor in Hover," NASA TM-81232, Sept. 1981.

[8]Srinivasan, G. R., Raghavan, V., and Duque, E. P. N., "Flowfield Analysis of Modern Helicopter Rotors in Hover by Navier-Stokes Method," Paper presented at the American Helicopter Society–Royal Aeronautical Society International Technical Specialists Meeting on Rotorcraft Acoustics and Rotor Fluid Dynamics (Philadelphia, PA), Oct. 1991.

[9]Boxwell, D. A., Yu, Y. H., and Schmitz, F. H., "Hovering Impulsive Noise: Some Measured and Calculated Results," *Vertica,* Vol. 3, No. 1, 1979, pp. 35–45.

[10]Purcell, T. W., "A Prediction of High Speed Rotor Noise," AIAA Paper 89-1130, July 1989.

[11]Caradonna, F. X., Laub, G. H., and Tung, C., "An Experimental Investigation of the Parallel Blade-Vortex Interaction," Paper No. 4, *Proceedings of the Tenth European Rotorcraft Forum* (The Hague, The Netherlands), Aug. 1984.

[12]Caradonna, F. X., Lautenschlager, J. L., and Silva, M. J., "An Experimental Study of Rotor-Vortex Interactions," AIAA Paper 88-0045, Jan. 1988.

[13]Srinivasan, G. R., McCroskey, W. J., and Baeder, J. D., "Aerodynamics of Two-Dimensional Blade-Vortex Interaction," *AIAA Journal,* Vol. 24, No. 10, 1986, pp. 1569–1576.

[14]Schmitz, F. H., Boxwell, D. A., Splettstoesser, W. R., and Schultz, K. J., "Model Rotor High-Speed Impulsive Noise: Full-Scale Comparisons and Parametric Variations," *Vertica,* Vol. 8, No. 4, 1984, pp. 395–422.

Correlation of Conical Interactions Induced by Sharp Fins and Semicones

Xue-Ying Deng* and Jin Hua Liao†
Beijing University of Aeronautics and Astronautics, Beijing 100083, People's Republic of China

Introduction

The conical interactions are one important type of swept shock wave and boundary-layer interactions and have been extensively studied.[1,2] Most research has studied the conical interaction behaviors induced by individual shock generators such as swept compression corner, sharp fin, semicone, and so on.[1,2] However, their correlative behaviors—which means their common interaction features induced by dissimilar shock generators—have been less studied. Settles and Lu[3] were the first to make conical correlation induced by unswept sharp fins and swept sharpfins at $M_\infty = 2.95$. Settles and Kimmel[4] also tried to correlate quasiconical interaction behaviors generated by four types of dissimilar shock generators at $M_\infty = 2.95$. This Note studies the correlative behaviors induced by sharp fins and semicones and extends the previous conical similarity to the condition of varying freestream Mach number, especially in the low Mach number range. Furthermore, it demonstrates that the inviscid shock strength is a dominant parameter for the conical interactions.

Experimental Procedures

All tests were carried out in a G-3 supersonic wind tunnel with a test section of 54.8×47.0 cm^2 at Beijing University of Aeronautics and Astronautics (BUAA). A flat plate of 54.6×90 cm^2 was mounted in the test section horizontally, and the sharp fin or semicone model was attached to it. Tests were conducted at $M_\infty = 1.79$, 2.04, and 2.50, keeping the same Reynolds number $Re = 2.4 \times 10^7$/m. The boundary layer on the plate was tripped by the sand band with sand size of 80#. And this sand band with a 3 mm width is attached on the plate 5 mm from the leading edge of the plate. The fin and semicone models were placed 650 mm from the model apex to the leading edge of the plate. Undisturbed boundary-layer profiles in the test region were surveyed along the plate centerline using Sun-Childs wall-wake[5] curvefit to the survey data. And these survey results showed[6] that those profiles agree with wall-wake law well with a wake strength of $\pi = 0.55 \sim 0.67$. The incoming boundary layer overall, displacement, and momentum thicknesses at the position 650 mm from the leading edge of the plate were $9.41 \sim 9.39$ mm, $1.97 \sim 2.35$ mm, $0.68 \sim 0.59$ mm, respectively, for the test Mach numbers.

The sharp fin model was tested at angles of attack 6, 8, 10, 12, 16, and 20 deg for all Mach numbers, except the largest angle at $M_\infty = 1.79$ was limited by tunnel stall. Three semicone models with half-angles of 20, 25, and 30 deg were tested.

The present experiments consider the mean footprints of three-dimensional interactions as revealed by the kerosene-lampblack streak method. The upstream influence line and primary separation line in the interaction region can be detected from it.

Results and Discussion

A typical surface flow pattern of interaction with sharp fin or semicone is sketched in Fig. 1. It shows the conical symmetry feature for both shock generators. To select the flow region to be correlated with both shock generators, their inviscid flowfields might be considered. Both inviscid flow patterns downstream of the

Presented as Paper 91-1756 at the AIAA 22nd Fluid Dynamics, Plasma Dynamics, and Lasers Conference, Honolulu, HI, June 24–26, 1991; received July 26, 1991; revision received Aug. 3, 1992; accepted for publication Aug. 17, 1992.

*Professor, Fluid Mechanics Institute. Member AIAA.
†Graduate Student, Fluid Mechanics Institute.

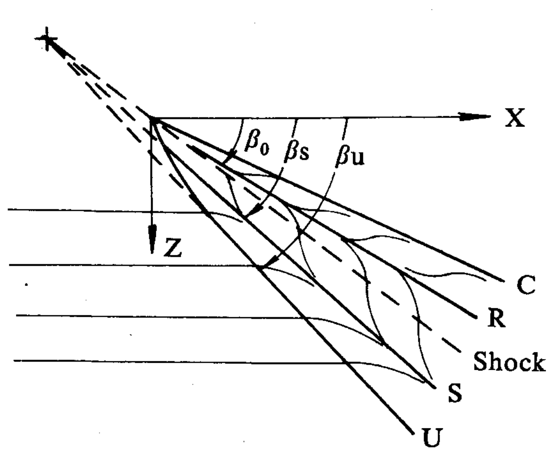

Fig. 1 Typical surface flow pattern: C, corner line of fin or semicone; Shock, intersection of shock and plate; S, primary separation line; U, upstream influence line; and R, reattachment line.

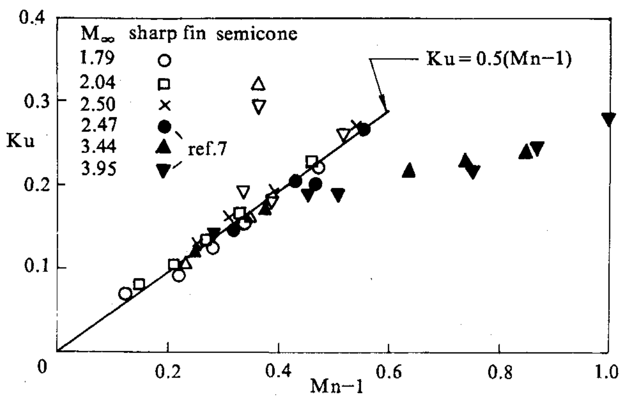

Fig. 2 Slope of upstream influence vs (Mn − 1).

shock wave are completely different from each other. But in the region upstream of the inviscid shock of both generators, the flow mainly interacts with the shock and is weakly affected by the shock generator itself. Therefore, the flow behaviors in this regime should be correlated well. The upstream influence line and separation line are the main flow properties in this flow interaction region.

Present experimental data show that the slope of the upstream influence line $Ku = tg(\beta u - \beta_0)$ can be correlated with inviscid shock strength $Mn(Mn = M_\infty \sin \beta_0)$ very well at three Mach numbers of 1.79, 2.04, and 2.50 for both sharp fin and semicone:

$$Ku = 0.5(Mn - 1) \tag{1}$$

as shown in Fig. 2, where the test data from surface flow visualization measurements by Lu and Settles[7] are also included. In general, upstream influence behavior should be controlled by parameters of both inviscid shock parameters and turbulent boundary-layer properties. In the present experiments freestream Mach number variation affects both inviscid shock strength and turbulent boundary-layer properties. However, from this experiment's correlation, the variation of upstream influence with freestream Mach number M_∞ is only caused by inviscid shock strength, not by turbulent boundary properties. The upstream influence behavior is controlled by inviscid shock strength. On the other hand, the inviscid shocks in the shape generated by the sharp fin and semicone are different: the shock of the sharp fin is a plane and the semicone shock is a cone with a certain curvature. Such correlation of the sharp fin and semicone shows that the upstream influence is only determined by shock strength regardless of shock wave curvature.

It should be noted that the quantitative correlation formula Eq. (1) is only effective in low normal Mach number range. When the normal Mach number is higher, the curve of $Ku \sim (Mn - 1)$ tends to level off as Lu and Settles show in Fig. 2.

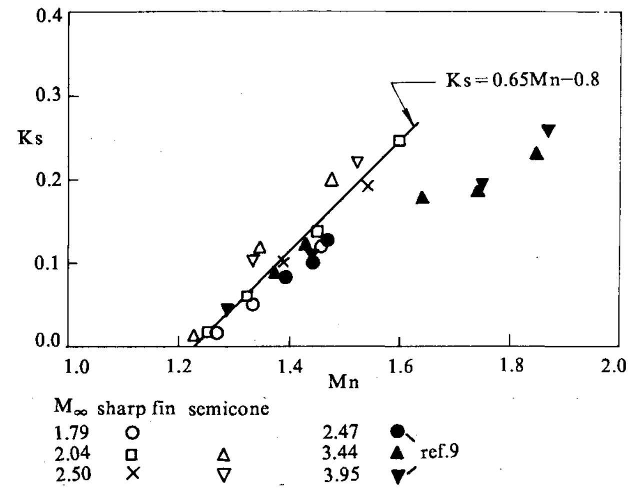

Fig. 3 Slope of separation line vs Mn.

Figure 3 shows that the slopes of primary separation lines induced by sharp fins and semicones were also correlated by inviscid shock strength very well at present three Mach numbers

$$Ks = 0.65Mn - 0.8 \tag{2}$$

This correlation indicates again that the flow behaviors upstream of the inviscid shock are dependent on shock strength only and independent of the shock curvature and Mach number of the turbulent boundary layer. $Ks = 0$ means that interaction flow is in an incipient separation state from Stanbrook's criterion.[8] It can be found from extrapolating the correlation curve to $Ks = 0$ in Fig. 3 that the condition of incipient separation is $Mn = 1.23$ or $(P_2/P_1)i = 1.6$. That is in agreement with Lu's value.[9]

Acknowledgments

This research was supported by the National Natural Science Foundation of China and the National Education Committee Sciences Fund. The authors express their sincere gratitude to G. S. Settles and F. K. Lu for their helpful discussions and for giving us the data from their tests.

References

[1]Settles, G. S., and Dolling, D. S., "Swept Shock Wave/Boundary Layer Interactions," *Tactical Missile Aerodynamics,* edited by M. J. Hemsch and J. N. Nielsen, Vol. 104, Progress in Astronautics and Aeronautics, AIAA, New York, 1986, pp. 297–379.

[2]Zheltovodov, A. A., Maksimov, A. I., and Shilein, E. K., "Development of Turbulent Separated Flows in the Vicinity of Swept Shock Waves," *The Interactions of Complex 3-D Flows,* edited by A. M. Kharitanov, Inst. of Theoretical and Applied Mechanics, Novosibirsk, Russia, 1987, pp. 67–91.

[3]Settles, G. S., and Lu, F. K., "Conical Similarity of Shock/Boundary Layer Interactions Generated by Swept and Unswept Fins," *AIAA Journal,* Vol. 23, No. 7, 1985, pp. 1021–1027.

[4]Settles, G. S., and Kimmel, R. L., "Similarity of Quasiconical Shock Wave/Turbulent Boundary-Layer Interactions," *AIAA Journal,* Vol. 24, No. 1, 1986, pp. 47–53.

[5]Sun, C. C., and Childs, M. E., "A Modified Wall-Wake Velocity Profile for Turbulent Compressible Boundary Layers," *Journal of Aircraft,* Vol. 10, No. 6, 1973, pp. 381–383.

[6]Deng, X. Y., Liu, Z. Z., and Cui, J. H., "Study of Upstream Influence in the Shock/Boundary Layer Interactions by Swept Compression Corners," *Proceedings of the 7th National Wind Tunnel Testing Conference,* Guang Zhai, China, Oct. 1987 (in Chinese), pp. 98–108.

[7]Lu, F. K., and Settles, G. S., "Upstream-Influence Scaling of Sharp Fin Interactions," *AIAA Journal,* Vol. 29, No. 7, 1991, pp. 1180,1181.

[8]Stanbrook, A., "An Experimental Study of the Glancing Interaction Between a Shock Wave and a Turbulent Boundary Layer," British Aeronautical Research Council, CP No. 555, London, July 1960.

[9]Lu, F. K., "Semi-Empirical Extension of McCabe's Vorticity Model for Fin-Generated Shock-Wave Boundary-Layer Interactions," *Proceedings of the 4th Asian Congress of Fluid Mechanics,* Hong Kong, Aug. 1989, pp. A170–A173.