Management of Turbulent Shear Layers in Separated Flow

W.W. Willmarth*
The University of Michigan, Ann Arbor, Mich.

R.F. Gasparovic†
Applied Physics Laboratory, Laurel, Md.

J.M. Maszatics‡, J.L. McNaughton,§ and D.J. Thomas‡
Bendix Aerospace Systems Div., Ann Arbor, Mich.

Abstract

AERODYNAMIC configurations with isolated regions of separated flow often produce unsteady flows with high levels of turbulent flow fluctuations. Some examples are: a bomb bay, an automobile window or sun roof, and a cavity flush with an aerodynamic surface. General principles are described for altering the aerodynamic configuration in order to control the free shear layer and reduce flow fluctuations. These principles were applied to an actual aerodynamic configuration. The flow fluctuations were measured in a wind tunnel and in flight. The root-mean-square velocity fluctuations beneath the shear layer were reduced to 2% of the stream velocity. Pressure fluctuations beneath the shear layer were 0.4% of the freestream dynamic pressure (of the order of the surface pressure fluctuations beneath a turbulent boundary layer on a smooth flat plate[1]).

Contents

More than 300 separate wind-tunnel tests to reveal general principles and particular methods for the management and stabilization of free turbulent shear layers associated with flow separation and reattachment over open cavities were conducted in the 2- × 2-ft and 5- × 7-ft wind tunnels of the Dept. of Aerospace Engineering at The University of Michigan. General concepts for management and stabilization of free shear layers were determined experimentally using a two-dimensional separated flow over a cavity in the wall of the 2- × 2-ft tunnel. Observations were made of the motion of tufts of goose down glued to fine wires in the midplane of the cavity and of pressure fluctuations in the cavity, detected with a Bruell and Kjaer ¼-in.-diameter microphone, Model 4135. A vortexlike flow circulation was observed within the cavity.[2] At any given flow speed, there was a particular cavity volume for which large periodic pressure fluctuations were produced within the cavity. Tests were made at 30 ft/s with an initial boundary-layer thickness of 1/15 of the 6-in. cavity width. Numerous alterations of the configuration were made and tested. Reduced flow fluctuations were observed with porous fences normal to the surface well upstream of the cavity and a 45-deg porous flow deflector at the upstream edge of the cavity (see Fig. 1). The cavity flow was then a confusion of weak vortices and secondary flows.

The use of a deflector to control the shear layer in separated flow has been reported by Wolford[3] and Obremski et al.[4] The deflector provided a fixed separation point and elevated the shear layer. Flow fluctuations in the cavity were reduced because disturbances at reattachment were farther down stream. Flow disturbances at separation and reattachment were also reduced by thickening the shear layer so that velocity gradients were reduced. The fences rapidly produced a thick shear layer with a uniform distribution of turbulent scales. It was necessary to have the highest fence well upstream. This resulted in early production of large eddies which decay slowly and are then "chopped up" and "scrambled" by the downstream fences.

After the initial studies, tests were run in the 5- × 7-ft tunnel to reduce the mean and fluctuating flow velocities within an optical system housing with an ellipsoidal nose. Figure 2 is a plane section of the housing which is of considerable aerodynamic complexity, owing to the possibility of interaction between the separated flow regions on either side of the housing. Measurements of pressure fluctuations within the housing were made with a Bruell and Kjaer microphone, Model 4138. Two constant-temperature hot-film probes, Thermosystems Model 1054 B-1, were mounted in the cavity beneath the openings. Tufts of yarn were fastened to the exterior surface of the housing and to a grid of wires within the housing. The interior and exterior surface of the housing was fitted with flush pressure taps. Two impact pressure rakes were mounted at the downstream lip of the cavity on either side of the housing. A maximum of 700 ft^3/min of air could be admitted at the rear of the cavity or injected at high speed in an annular jet along the upstream lip of the cavity.

When the unmodified housing was first tested, extremely severe periodic pressure fluctuations were observed within the

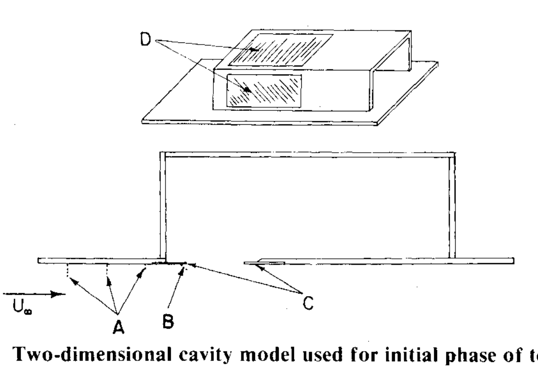

Fig. 1 Two-dimensional cavity model used for initial phase of tests: A—porous fences 70% open area, 1.5, 1.0, and 0.5 in. high and 4 in. apart; B—porous deflector 30% open area, 0.5 in. high; C—aluminum sheet, 0.062 in. thick; D—plastic windows.

Received Sept. 13, 1977; revision received April 4, 1978. This synoptic is based upon two reports, BSR 4188 and BSR 4230 of the Bendix Aerospace Systems Division. The full papers are available from National Technical Information Service, Springfield, Va. 22151 as N78-21401 and N78-21402, respectively, at the standard price (available upon request).

Index categories: Jets, Wakes and Viscid-Inviscid Flow Interactions; Nonsteady Aerodynamics.

*Professor, Aerospace Engineering. Associate Fellow AIAA.
†Project Manager.
‡Staff Engineer.
§Supervisor, Surveillance and Information Systems.

Table 1 Flow parameters in the cavity as a function of inclination angle to the stream ψ during wind-tunnel tests (configuration is that shown in Fig. 2, $U_\infty \simeq 300$ ft/s)

ψ deg.	u'/U_∞ [a]	u_{max}/U_∞	$\bar{U}/U_\infty$	p'/q	$\Delta p/q$ [b]
0	0.012	0.024	0.0096	0.0081	0.0016
±5	0.004	0.008	0.005	0.0063	0.0032
±10	0.021	0.06	0.03	0.0081	0.0032

[a] Prime indicates rms.
[b] Here Δp is the maximum static pressure variation in the cavity among all the static pressure taps.

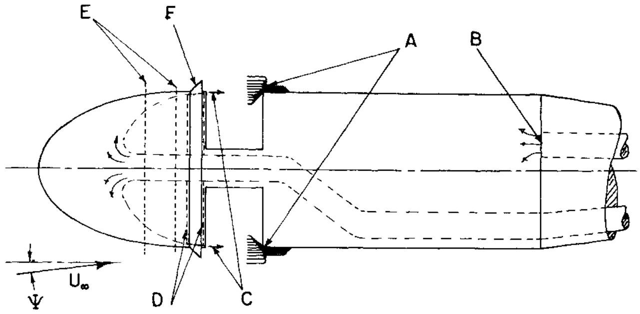

Fig. 2 Optical system housing used for 5- × 7-ft wind tunnel tests in final configuration: A—impact pressure rakes; B—air inlet (4 in. diam); C—annular air jet; D—bulkhead; E—porous fences, 46% open area, 1.4 and 0.66 in. high and 4 in. apart; F—45 deg solid deflector, 1.5 in. high.

cavity (and throughout the wind tunnel). At a speed of 250 ft/s, the sound pressure level in the cavity was 159 dB (re: 2×10^{-10} bar). Karamcheti[5] has reported pressure fluctuations of this order of magnitude associated with flow over rectangular cavities in a plane surface. When the flow was inclined to the axis of the housing more intense periodic pressure oscillations began at lower speeds and were accompanied by severe buffetting.

Periodic flow fluctuations were supressed by an internal bulkhead at the upstream edge of the cavity openings and a 45-deg solid deflector on the surface (see Fig. 2). Many aerodynamic modifications were tested in a search for those which minimized the cavity flow fluctuations. The final configuration consisted of the original housing fitted with an internal bulkhead, a solid flow deflector, and two porous fences (see Fig. 2).

Tests were also made at various inclinations to the freestream. Flow fluctuations within the housing were a minimum when the flow inclination angle, ψ, was 5 deg and 200 cfm of air was introduced in the aft end of the cavity. Disturbances were reduced because the internal airflow and slight asymmetry stabilized the unsteady reattachment flow. Table 1 is a summary of the measured data. When the housing was inclined at 15.5 deg to the stream, the windward reattachment region approached the downtream edge of the window. The velocity fluctuations within the housing were large, of the order of 40 times their minimum value at 5 deg inclination to the stream.

Flight tests of the configuration shown in Fig. 2 were made with the housing mounted on the upper part of the nose radome of a Lockheed RP-3A aircraft. Very large mean and fluctuating flow velocities occurred withing the housing. The mean internal velocity was of the order of 70% of the freestream velocity. A model of a portion of the nose radome and housing (see Fig. 3) was tested in the 5- × 7-ft wind tunnel to determine the cause of the large mean flow within the cavity.

The tests showed that the radome beneath the lower window of the housing caused the lower shear layer to curve sharply upward and enter the housing through the lower window and leave through the upper window (see Fig. 3).

Table 2 Measured minimum and maximum velocities in flight at various altitudes and flight attitudes (configuration of Fig. 4, $U_\infty \simeq 300$ ft/s)

	u'/U_∞ [a]	$u_{max.}/U_\infty$	$\bar{U}/U_\infty$
Maximum	0.0034	0.042	0.04
Minimum	0.0017	0.00676	0.0135

[a] Prime indicates rms.

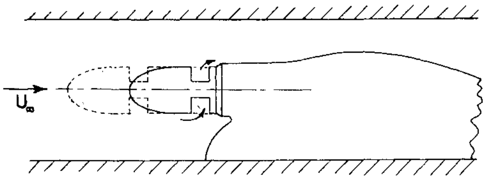

Fig. 3 Optical system housing mounted in wind tunnel on a model of a portion of nose radome of Lockheed RP-3A aircraft. Solid line is initial configuration with upward flow into lower window and out of upper window. Dashed line is final configuration 26 in. forward without upward flow into lower window.

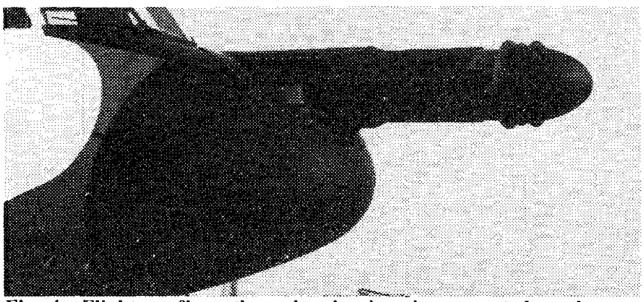

Fig. 4 Flight configurations showing housing mounted on the nose radome of Lockheed RP-3A aircraft

The severe velocity fluctuations and the mean flow through the cavity were eliminated by extending the housing farther upstream. Satisfactorily low mean and fluctuating velocities were obtained with a 26-in. extension of the housing (see Fig. 3, dashed lines).

The new configuration, Fig. 4, was tested in flight. The mean and fluctuating velocities measured within the housing at angles of inclination less than 10 deg are summarized in Table 2.

Acknowledgment

This work was supported by the Department of the Navy. The authors' views do not necessarily represent the position of the Department of the Navy. We wish to acknowledge the assistance of D. Draxler and J. Perry, who conducted the initial phase of the test program. We are also indebted to C.J. Iott, D.R. Glass, D. Geister, and L. Griffin for their assistance in preparing and conducting the wind-tunnel test program and to C.V. Nelson, R.G. Chappell, and L.D. Tubbs for their assistance in conducting the flight test program.

References

[1] Willmarth, W.W., "Pressure Fluctuations Beneath Turbulent Boundary Layers," *Annual Review of Fluid Mechanics,* Vol. 7, 1975, pp. 13-38.

[2] Roshko, A., "Some Measurements of Flow in a Rectangular Cutout," NACA TN 3488, Aug. 1955.

[3] Wolford, R.D., "Skyscraper Airborne Radiation-Measuring System," Bendix Systems Division of Bendix Corp., Rept. No. BSR-445, Feb. 1961.

[4] Obremski, H.J., Niessing, W.J., and Thomas, D.R., "TRAP-MATS," Aircraft Modification Program Phase 1 R&D Test Report; Martin Marietta Corp., Baltimore Div., Rept. ER 14862, Sept. 1969.

[5] Krishnamurty, K. "Acoustic Radiation from Two-Dimensional Rectangular Cutouts in Aerodynamic Surfaces," NACA TN 3487, Aug. 1955.