Performance and Exit Distortion of Diffusers as Determined by Force Measurements

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Theme

THE over-all performance of subsonic diffusers may be characterized in various ways. Among the integral parameters most used for this purpose are the static pressure rise coefficient (C_{ps}) and various indices of distortion describing nonuniformity at the diffuser exit. C_{ps} is defined as $(p_2 - p_1)/q_1$, where p is wall static pressure, q_1 is dynamic pressure based on inlet mean velocity and 1 and 2 refer to inlet and exit stations, respectively. It is proposed here that the force corresponding to the integrated exit impulse (measurable on a thrust stand) may be used to: a) define a vector exit impulse coefficient ($\mathbf{C}_I$) as an alternate to C_{ps}, and b) define a distortion index (Ψ). These coefficients are conceptually clear, applicable to complex geometries and flowfields, and well-suited to complement control volume analyses. They also offer considerable experimental advantages such as insensitivity to the presence of separation and three-dimensional flow, elimination of the need to determine flowfield details, and the instantaneous indication of a meaningful integral quantity.

Force and conventional pressure/flow-rate measurements were made on a set of nine diffusers, from which the proposed impulse coefficients were evaluated along with other, conventional integral performance parameters. The instrumentation, methods, and accuracy of the technique are described, and the results are compared, discussed, and complemented by flowfield measurements. It is concluded that the technique is feasible and convenient to use. It offers a new avenue of utilization for thrust stands for the development and testing of diffusers and nozzles.

Contents

The measurement of subsonic diffuser performance in the often unavoidable stalled flow modes is somewhat problematical. The static pressure rise coefficient is ambiguous because of large radial and axial pressure gradients[1] near both inlet and exit stations under such conditions. The exit distortion coefficients presently in use are not theoretically predictable nor are they likely to be in the near future.

A theoretically sound answer for both problems is established by using force measurements. The force sensed by the axial load cell in a static thrust stand (Fig. 1) is essentially equal to the exit impulse integrated over a suitably defined exit surface since the inlet flow is normal to the axis and is isolated by clearance flows. This quantity may be used to define an "exit impulse coefficient" as:

$$\mathbf{C}_I = \bar{\rho}_1 A_1 \mathbf{B}/G^2 \tag{1}$$

where ρ is density, A is cross-sectional area, $\mathbf{B}$ is the measured force and G is the mass flow. An equivalent expression shows the physical significance more clearly:

$$\mathbf{C}_I = (\bar{\rho}_1 \bar{u}_1{}^2 A_1)^{-1}\left[\int_{A_2}(p-p_a)\,d\mathbf{A} + \int_{A_2}\rho\mathbf{u}\mathbf{u}\cdot d\mathbf{A}\right] \tag{2}$$

where subscript a refers to ambient conditions.

The $\mathbf{C}_I$ is thus the ratio of the actual, integrated exit impulse to a nominal *inlet* impulse. It is a true integral parameter, not dependent on any local measurement that may be subject to localized irregularities. The load cell reading is always precisely interpreted by the square bracket in Eq. (2), even if the flow is three-dimensional or flow separation exists. There is a possibility of redundant control measurements since $\mathbf{C}_I$ can be evaluated either from load cell data or from detailed flowfield surveys at the exit (no such redundancy exists for C_{ps}).

Referring the measured exit impulse to a nominal *exit* impulse, one obtains a measure of exit distortion:

$$\Psi \equiv (\bar{\rho}_2 \bar{u}_2{}^2 A_2)^{-1}\left[\int_{A_2}(p-p_a)\,d\mathbf{A} + \int_{A_2}\rho\mathbf{u}\mathbf{u}\cdot d\mathbf{A}\right] \tag{3}$$

For nearly incompressible flow, Ψ is conveniently approximated by $(A_2/A_1)\mathbf{C}_I$; this quantity is designated as ψ. Neglecting the small pressure contribution from the first integral and consider-

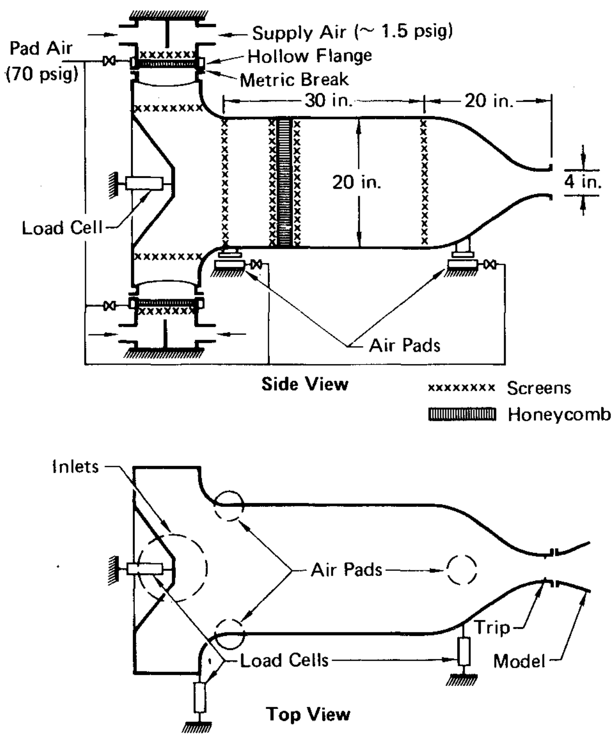

Fig. 1 Schematic of experimental equipment.

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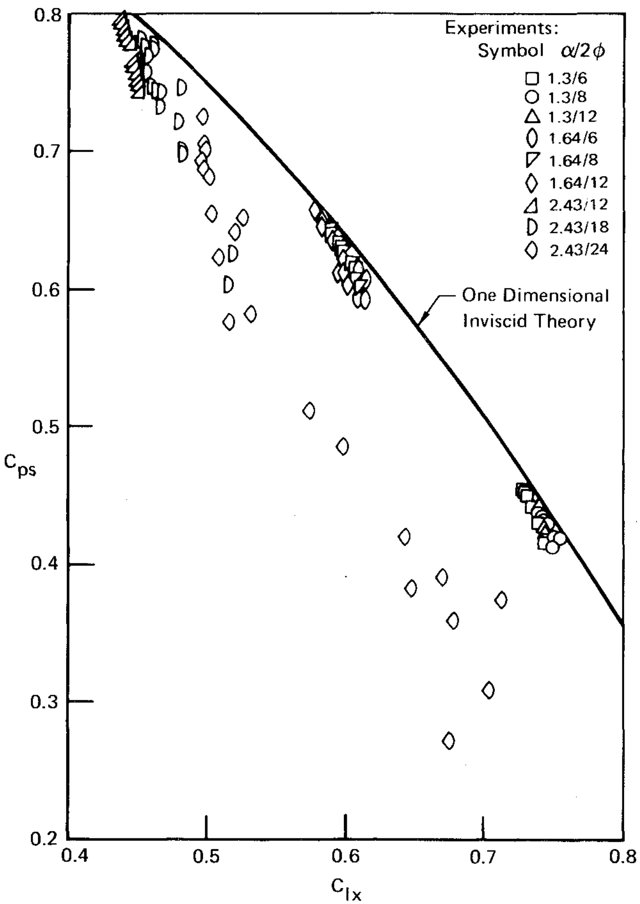

Fig. 2 Relation between static pressure rise and exit impulse coefficients.

ing incompressible flow and axial (x) components only, we have:

$$\psi_x \simeq 1 + \frac{1}{\bar{u}_2{}^2 A_2} \int_{A_2} (u-\bar{u})^2 \, d\mathbf{A} \tag{4}$$

ψ_x is clearly equal to or greater than unity. The excess over unity represents the variance of the mean velocity distribution which is a frequently used and well understood measure of nonuniformity.

It is shown that for incompressible, steady flow in a straight diffuser with uniform inlet velocity and pressure distributions, the following relation connects the major performance parameters:

$$\frac{\alpha^2}{2+\alpha^2}\left(C_{ps}+C_{pt}+\frac{3}{\alpha}C_{Ix}\right)=1 \tag{5}$$

where $\alpha = A_2/A_1$ and $C_{pt} = (\hat{p}_{t1}-\hat{p}_{t2})/q_1$; carets designate mass-flow weighted averages. Using Eq. (5) as a check, and measuring C_{ps}, C_{pt}, and C_{Ix} by independent means gave residuals of 0.7–2.5% thus verifying the data for the six attached flow cases reported. Better performance is described by higher C_{ps} and by smaller C_{Ix} (or ψ_x) values.

Feasibility of the concept was demonstrated through comparative measurements[2] on nine straight, conical diffusers of 4 in. inlet diam, at inlet Reynolds numbers of 0.15 to 0.75×10^6 and inlet Mach numbers less than 0.3. Area ratios were 1.3, 1.64, and 2.43, and cone angles (2ϕ) were 6, 8, 12, 16, and 24 degrees. Inlet static pressure was measured 0.75 radius upstream of the inlet station, and exit pressure was assumed to be atmospheric. The boundary layer approaching the inlet was laminar, and the momentum thickness varied from 0.015–0.005 in., decreasing with increasing flow rate. C_{ps} and $\mathbf{C}_I$ values were measured for the available range of Reynolds numbers in each case, and C_{pt} values were determined in cases of unseparated exit flow from pitot tube traverses.

Typical experimental data are shown in Fig. 2 as a relation between C_{ps} and C_{Ix}. The results agree with expectations. The large area-ratio diffusers ($\alpha = 2.43$) suffer from considerable total pressure losses which account for the large deviation from the inviscid prediction. In these cases, significant radial pressure gradients exist at both inlet and exit stations rendering C_{ps} values based on local wall pressures questionable. On the other hand, C_{Ix} strictly corresponds to Eq. (1) in all cases.

Reference 3 contains a detailed investigation of the effect of inlet flow conditions on diffuser performance utilizing this technique. Further refinements of data interpretation also are described. It is believed that this technique can be adapted to the study of flow distortion in the subsonic diffusers of supersonic inlets. Significant aspects of the transient flow behavior associated with peak recovery at constant length can also be studied effectively by the proposed technique.

References

[1] Sprenger, H., "Experimental Investigations of Straight and Curved Diffusers," Mitteilungen des Institutes für Aerodynamik, Vol. 27, Zurich, 1959. Translation by Technical Information and Library Service, Ministry of Aviation, England, No. TIL/T.5134, 1962.

[2] Sajben, M., Kroutil, J. C., Sedrick, A. V., "Performance and Exit Distortion of Diffusers as Determined by Force Measurements," Paper MDRL 74-2, McDonnell Douglas Corp., St. Louis, Mo., 1974.

[3] Sajben, M., Kroutil, J. C., Sedrick, A. V., and Hoffman, G. H., "Experiments on Conical Diffusers with Distorted Inflow," AIAA Paper 74-529, Palo Alto, Calif., 1974.