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Comparison of Conventional and Force-Based Distortion Index Measurements

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STEADY flow nonuniformities at the diffuser/compressor interface of airbreathing inlets significantly influence the surge behavior of jet engines. The proper characterization of such distortions is recognized to have an important bearing on both inlet and compressor design.[1,2] Many definitions of descriptive indices have been proposed, but few have gained wide acceptance.

In a recent paper,[3] the suggestion was made that an indicator of velocity nonuniformity can be deduced from the measurement of force associated with the integrated impulse $(p+\rho u^2)$. Strong theoretical and practical reasons favor such an index,[3] one of which is that it correlates well with one of the most widely accepted indicators of distortion, and valid comparisons therefore can be made with existing data presented in terms of other types of indices. Experiments supporting this claim are described in this note.

The distortion index proposed here relies on force and flow rate measurements that are made routinely in thrust stands to determine nozzle flow and thrust coefficients. If the experiment is arranged appropriately,[3] the index can be computed as

$$\psi_x = \bar{\rho} A F_x / \dot{m}^2 \tag{1}$$

where $\bar{\rho}$ is the area-averaged density, A is the exit area (assumed plane and normal to the x axis), $\dot{m}$ is the mass flow and F_x is the x component of the force corresponding to the impulse integrated over A.

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The integral of the impulse contains a contribution from the static pressure. The test usually can be arranged such that this contribution is small; the following approximate equality is then valid

$$\psi_x - 1 \cong \frac{1}{\rho \bar{u}^2 A} \int_A \rho (u-\bar{u})^2 dA \tag{2}$$

Equation (2) shows that $(\psi_x - 1)$ is zero for uniform flows and is increasingly greater than zero as the velocity distribution becomes more nonuniform. The index is appropriate for preliminary, configuration screening studies. More complex indices, reflecting radial and circumferential dependencies, are used for detailed inlet evaluations.

The proposed index offers both theoretical and practical benefits. Its definition is rigorously compatible with the momentum equation and therefore is well suited to complement theoretical calculation, especially integral methods. The required measurements are routine on conventional thrust stands. Flowfield details need not be determined, eliminating problems of flow obstruction by probe rakes. The number of transducers is reduced greatly, simplifying both calibration and data recording procedures. The measurement is insensitive to flowfield complexities such as intense turbulence or separation which generally prevent a reliable interpretation of signals from conventional total pressure probes.

Definitions of conventional indices do not permit derivation of theoretical correlations with ψ_x. To determine the empirical correlation, a test series was conducted in which three different indices were measured simultaneously.

Two conventional indices were chosen for comparison with ψ_x, both of which require total pressure measurements at 48 positions over the exit plane, in a manner customary in inlet testing. The first index, designated as ζ, is defined as

$$\zeta = (p_{t,\max} - p_{t,\min}) / \bar{p}_t \tag{3}$$

where $p_{t,\max}$ $(p_{t,\min})$ is the maximum (minimum) indicated total pressure from the set of 48 and $\bar{p}_t$ is the area average of all readings. All pressures are time-averaged values.

ζ measures nonuniformity in terms of total pressure whereas ψ_x is defined in terms of velocity, resulting in different types of dependence on the (cross-sectional averaged) Mach number. For low and moderate Mach numbers $(M<0.3)$, the relationship between the two indices is described approximately by the following relation

$$\zeta / \bar{M}^2 \cong C\left[(u^2_{\max} - u^2_{\min}) / \bar{u}^2 \right] \tag{4}$$

where C is a constant and $\bar{M}$ and $\bar{u}$ are averages of Mach number and axial velocity over the exit cross section, respectively. The bracket in Eq. (4) depends on the normalized velocity distribution, as does ψ_x. It follows that the quantity to be compared with ψ_x is not ζ but the ratio $\zeta/\bar{M}^2$.

A second index chosen for comparison, one of the most complex indices currently in use, is defined (in the notation of Ref. 4) as

$$K_{a2} = K_\theta + bK_{ra2} \tag{5}$$

where K_θ characterizes the circumferential and K_{ra2} the radial nonuniformities. The coefficient b is a weighting factor, dependent on the engine type. Details of the rather complex definitions can be found in Ref. 4. Data appropriate to the Pratt & Whitney F-100-FW-100 engine were used. The normalization employed in computing K_{a2} is such that K_{a2} is directly comparable with ψ_x. (Division by $\bar{M}^2$ is not necessary, as in the case with ζ.)

The measurements were conducted using seven different, axisymmetric diffusers, whose dimensions are given in Table 1. Reynolds number based on throat diameter ranged from 0.3×10^6 to 1.3×10^6. Throat Mach numbers ranged from 0.15 to 0.6. The flow exhausted to the atmosphere. No hub was employed at the diffuser exit, and an additional (49th) total pressure probe was located on the axis. The

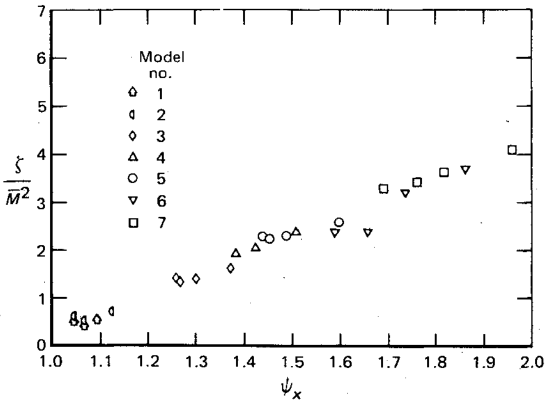

Fig. 1 Comparison of $\zeta/\bar{M}^2$ with ψ_x for clean diffusers (first test series). Values are given for four different inlet Mach numbers ($\bar{M}_1 = 0.15, 0.3, 0.45, 0.6$) with each configuration.

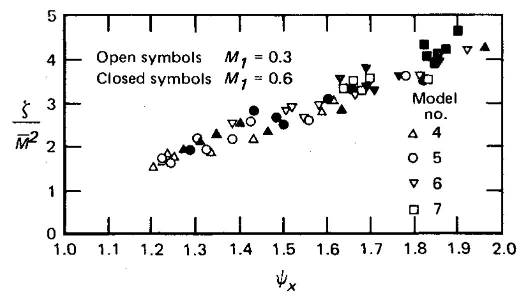

Fig. 2 Comparison of $\zeta/\bar{M}^2$ with ψ_x for diffusers with boundary-layer control (second test series). Repeated points with the same symbol correspond to different boundary-layer control arrangements.

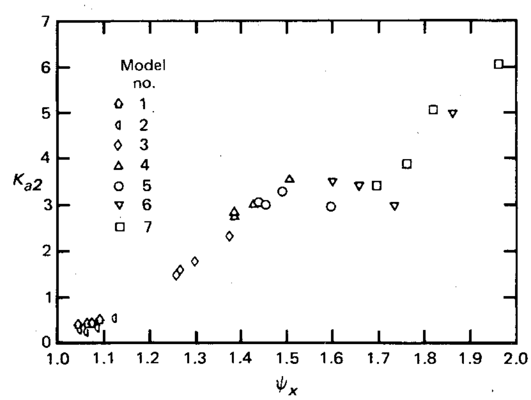

Fig. 3 Comparison of K_{a2} with ψ_x for clean diffusers (first test series). Values are given for four different inlet Mach numbers ($\bar{M}_1 = 0.15, 0.3, 0.45, 0.6$) with each configuration.

measurements were made using the facility described in Ref. 3.

In the first test series, a trip located 25 mm upstream of the diffuser inlet produced a turbulent boundary layer at the throat. In the second series, passive boundary-layer control devices of various sizes but of the same type were employed near the throat, all of which produced turbulent boundary layers. Details of the devices are irrevelant for the purposes of this note and will not be given here.

Figures 1 and 2 show the correlation between the indices $\zeta/\bar{M}^2$ and ψ_x for the first and second test series, respectively. The conclusion is that excellent correlation exists between the

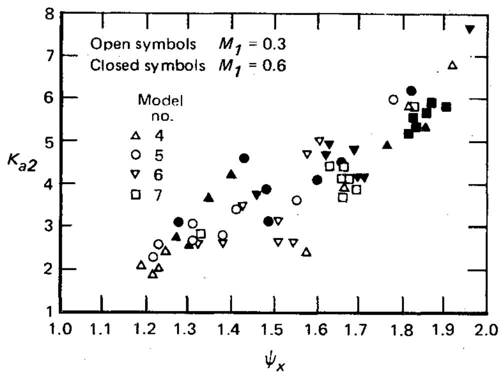

Fig. 4 Comparison of K_{a2} with ψ_x for diffusers with boundary-layer control (second test series). Repeated points with the same symbol correspond to different boundary-layer control arrangements.

Table 1 Diffuser dimensions

Model no.	Length to inlet diam ratio L/D_1	Area ratio A_2/A_1	Included equivalent cone angle, 2ϕ	Remarks
1	4.01	1.64	8	
2	2.67	1.64	12	Conical diffusers
3	5.32	2.43	12	
4	4.76	2.43	15	
5	4.00	2.43	18	Smoothly contoured diffusers with straight axes
6	3.36	2.43	23	
7	2.83	2.43	31	

[a] Inlet diam is 10.2 cm for all models.

two indices for both test series. Data for various Mach numbers collapse into a single curve, verifying the Mach number scaling used for ζ [Eq. (4)].

Figures 3 and 4 show comparisons between ψ_x and K_{a2}, again for the first and second test series. There is a consistant trend of proportionality despite the drastically different natures of the two indices. The scatter is noticeably larger in the range $1.4 < \psi_x < 1.7$ for both test series. No explanation is offered for this behavior; note, however, that ψ_x is more sensitive than K_{a2} to the flow pattern changes occurring in this range.

The final conclusion is that distortion data, in terms of the force-based index, compare well with distortion data given in terms of ζ. Both parameters gave essentially the same ranking for a given class of configurations and given Mach numbers despite the use of different facilities and test procedures. The force method is thus a feasible alternative for obtaining distortion information and may offer considerable savings in both time and cost.

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