tive of an SST operating at high Mach number high-altitude cruise. Extensive research and development must be accomplished before such results could be demonstrated in a modern annular aircraft combustor operating over the required LTO duty cycle. A potential Advanced Low Emission Annular Combustor is shown schematically in Fig. 10. The main potential problems of such a combustion system are:

1) The Advanced Low Emission Combustor may be appreciably larger than current combustors. CO consumption is improved by increased size. Increased size increases NO_x emissions, however. Reduced loading appears to improve the over-all tradeoff.

2) Variable geometry of some type is a definite requirement to maintain ultra low emissions over the operating range. This is obviously accompanied by increased control complexity and cost.

3) Variable geometry compensation is also required for flame stability over the operating range.

4) A pilot fuel system may be required to obtain adequate ignition and relight capabilities.

5) Fuel vaporization is a problem at low inlet temperature. Solutions to this problem result in complex and costly designs.

6) Future engines may have limited turbine inlet temperature and possibly a limited cycle-pressure ratio as a result of more stringent emission control. Such restrictions would reduce SFC performance.

Balancing these problem areas is 90% simultaneous CO-NO_x emission reduction. Other advantages for the Advanced Low Emission Combustor are: 1) No turbine erosion from carbon particles. 2) Improved turbine inlet temperature pattern due to elimination of hot zones, achieved with premix systems. 3) Reduced radiation, which reduces combustor cooling requirements and increases durability. 4) More amenability to analysis than the conventional combustor. After the basic design technology is established, this will lead to greatly reduced development requirements.

VI. Conclusions

Recently issued EPA aircraft emission regulations will have a great influence on future combustor designs. Compliance with existing regulations can probably be achieved with modifications to conventional combustion systems. These modifications include airblast fuel preparation, optimized reaction volume, and possibly variable airflow fuel staging, or idle bleed. These types of changes optimize emissions from the conventional droplet combustion process. A major challenge is to retain the traditional combustor virtues in the modified designs.

Emission reductions of 90% can be made by abandoning the conventional droplet combustion process in favor of premixed-prevaporized combustion. Basic feasibility has been demonstrated in single can combustors. A major combustion challenge is to incorporate this Advanced Low Emission Combustor technology into annular aircraft combustors which also satisfy the traditional combustor requirements.

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P^3G—A New Dynamic Distortion Generator

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A Planar Pressure Pulse Generator (P^3G) was developed for use in quantitative evaluations of compression system response to large sinusoidal pressure oscillations over wide ranges of frequency. The P^3G is a mechanical device consisting of coaxial rotors and a stator with matched holes. Frequency of the generated pulses is controlled by rotor speed, and amplitude is controlled by varying axial rotor-to-stator spacing. Secondary flow is not required since the P^3G operates on compressor or engine airflow. Test data substantiate that the P^3G produces the following results. 1) High enough peak to peak amplitude discrete frequency pressure oscillations over the range of 40 to 800 Hz for use in compressor or engine stability testing. 2) Enough variation and control of peak to peak amplitude and frequency to obtain parametric data on compressor or engine surge characteristics. 3) Good sinusoidal waveform characteristics which generally exhibit harmonics of less than 20% of the fundamental amplitude. 4) Good wave planarity as measured by similarity of ring and rake peak to peak pressure amplitudes and phase.

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I. Introduction

MOST engine stability testing to date which addresses the effects of dynamic inlet distortion has been based on combined spatial and temporal distortions as typified in Fig. 1.

While such approaches can be quite representative of aircraft inlet environments, quantitative understanding of the engine response to the dynamic phenomena may be limited by the complexity of these combined distortions.

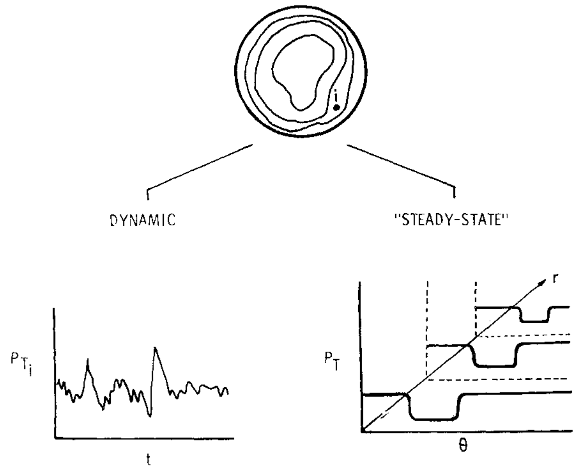

Fig. 1 Combined spatial and temporal distortion.

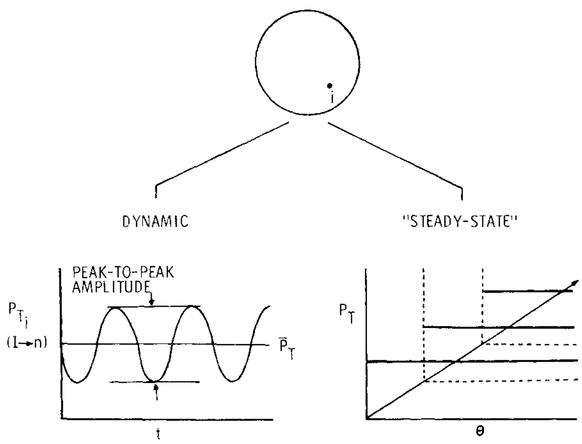

Fig. 2 Spatially uniform discrete frequency distortion.

Specifically, reliable deduction of the quantitative loss in engine surge margin due to the dynamic component of such combined distortions requires an applicable data bank accurately documenting steady-state distortion effects for a wide range of complex pressure distortion patterns. Furthermore, the spatial nonuniformity of such combined distortions generally defies the type of analytical studies required for minimizing adverse dynamic effects through aerodynamic design.

These complications suggest the desirability of eliminating both steady-state and dynamic spatial distortion for more in-depth studies of the temporal effects on engine stability. In theory, isolation of the temporal from spatial effects in dynamic distortion as typified in Fig. 2 can be accomplished through the use of discrete frequency distortion generator devices. Tests with such devices have been conducted previously.[1-4]

In practice, however, with few exceptions, data obtained with these discrete frequency generators have had limited impact on the problem of isolating temporal from spatial effects in dynamic phenomena. This has been due primarily to either low peak to peak pressure amplitude at the higher frequencies and/or significant departures from spatial uniformity. When peak to peak amplitudes are low, the resultant engine surge pressure ratio losses may be too small to accurately measure. Furthermore, influence coefficients such as surge margin loss per unit peak to peak amplitude determined at low amplitude values, may not linearly apply at the higher peak to peak amplitudes of actual concern. Spatial effects cloud the issue not only by their presence as an additional variable, the effects of which must be accounted for, but also by limiting the applicability of such data in comparison with necessarily more simplified analytical modelling results.

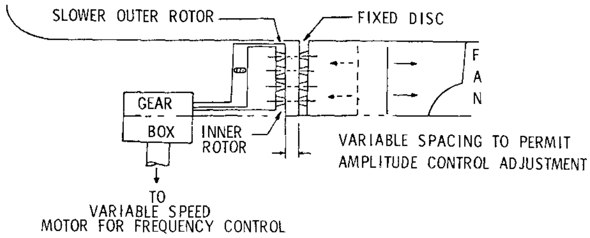

Fig. 3 Planar pulse generator concept.

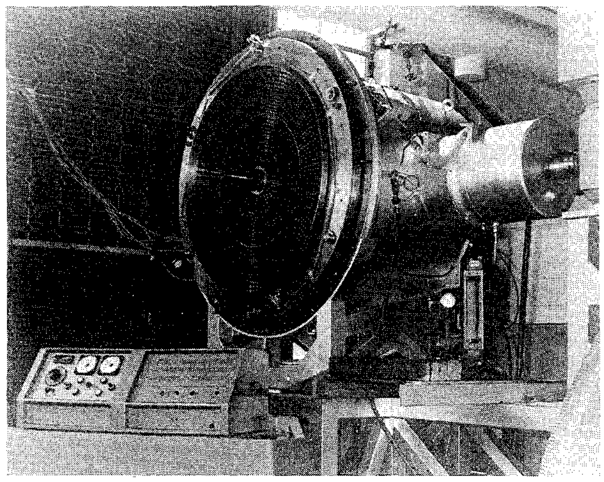

Fig. 4 P³G discharge side.

The P³G is a discrete frequency distortion generating device that not only produces high peak to peak amplitudes over a wide frequency range, but accomplishes this without the necessity for a secondary airflow system. The latter is a distinct facility advantage in that the cost of an additional high pressure air supply and total temperature matching problems with the primary engine flow are avoided.

II. Concept

Figure 3 is a simplified cross section of the P³G as installed in the bellmouth for fan stability testing. Sinusoidal inlet flow/pressure throttling is accomplished by a method very similary to a siren—chopping the airflow through the mating holes of a rotating disk and a stationary disk. The siren similarity ends there, however, because the P³G aerodynamic design is necessarily more sophisticated in order to minimize the steady-state pressure losses that do not contribute to the pulse generating phenomena, and to ensure uniform and planar waves. Furthermore, a choked condition exists at the airflow chopping plane so as to gain higher levels of output fluctuations. The full scale P³G is shown in Fig. 4 displaying its downstream, or emittance side.

The basic mechanical design is novel and innovative,§ yet the design levels are conservative. The mechanical design of the system tested consists of multiple rotors (all coaxial) with gear-controlled rotor speeds in inverse proportion to the number of holes in the radial rows in each of these rotating disks. Aerodynamic considerations dictated uniform hole sizing in the rotor which, in turn, necessitated the multiple rotor design. An axially translating stationary disk (stator) with mating holes to the rotating disks (rotor) provides a variable axial clearance between

§Acknowledgment of the special contribution made by W. H. Wilkinson and R. E. Robinson to the design and fabrication effort at Battelle Columbus Laboratories.

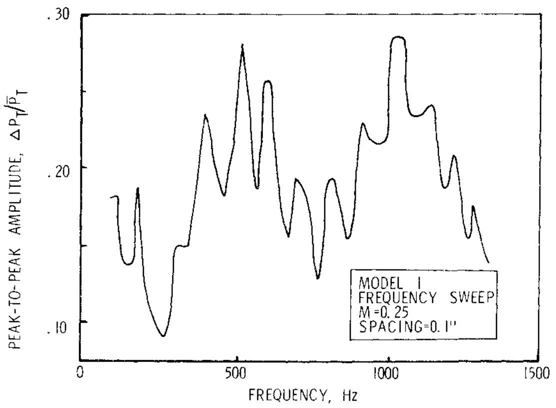

Fig. 5 Peak-to-peak amplitude as a function of frequency.

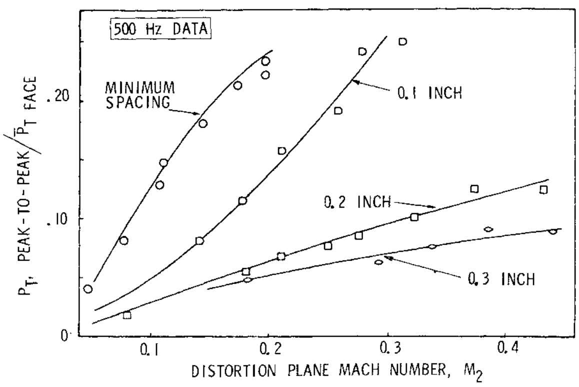

Fig. 6 Peak-to-peak amplitude as a function of Mach number and rotor/stator spacing. (No downstream choke).

the rotor and stator. Thus, the frequency of the air pulses generated is controlled by rotor speed, and the amplitude is controlled by the rotor-to-stator (R-T-S) spacing and the amount of airflow through the holes.

The rotor speed relationships and disk-to-disk hole opening/closing cycle phasing is accomplished in the drive assembly. Radial drive was ultimately chosen for minimizing the P^3G axial length and airflow blockage. Radial drive also provides compactness and serviceability.

The multiple rotor system has the potential flexibility for use with different size engines by addition or reduction of the number of concentric rotor rings. With this thought in mind, the full scale P^3G with a diameter of approximately 4 ft, was a 3 rotor system with capability for running 2 smaller diameter configurations.

For concept verification, two $\frac{1}{6}$ scale P^3G models were built and tested prior to the full scale design. Both scale models were dual rotor configurations. The first model (Model I) was tested in early 1971 and clearly demonstrated the ability to produce high peak to peak amplitude over a wide frequency range. Model II was subsequently designed to reduce the steady-state pressure losses and was tested later in 1971. These results were used in the triple rotor full scale P^3G design which has subsequently been utilized in fan component stability investigations.[5]

III. Peak Amplitude Capability

Model I amplitude vs frequency (sweep) characteristic at a fixed rotor-to-stator spacing (R-T-S) and an instrumentation plane duct Mach number of 0.25 is shown in Fig. 5. The duct Mach number as quoted is an average duct Mach number as computed directly from the steady-state instrumentation. On this basis, the conditions of Fig. 5 correspond to low corrected flow operation of a turbofan engine. Figure 5 thus demonstrates the capability for achieving high peak to peak amplitude not only over a wide frequency range, but at the more ordinarily challenging conditions of low corrected flow. This is accomplished by appropriately sizing the holes in the rotor-stator system.

Analysis has shown that the indicated major variations of the peak amplitudes with frequency as shown in Fig. 5 are primarily the result of duct resonance phenomena and related harmonics of the standing pressure waves. Thus the peaks generally correspond to conditions for which the fundamental is amplified and the valleys represent conditions for which it has been attenuated.

Acoustically similarly conditions for the pressure pulses require that the parameter fL/a be the same value for the $\frac{1}{6}$ scale models and the full scale P^3G. Rather than run the scale model at 6 times the full scale rotor RPM connected to a $\frac{1}{6}$ scale length duct, it was decided for mechanical, aerodynamic, and measurement accuracy reasons to operate the scale models at full scale RPM connected to a full scale length duct. Consequently, the data presented as measured in Fig. 5 is for all practical purposes what would be expected full scale. Peak to peak amplitudes in the range of 15 to 20% were generally achieved to frequencies as high as those corresponding to approximately 8 to 10 times the design rotor revolution speed in many fan compression units for current turbofan engines. The 15 to 20% peak to peak amplitude is considered adequate for reasonably accurate determination of engine surge pressure ratio loss based on analogy with the magnitude of surge pressure ratio loss for $(P_{T\,\max} - P_{T\,\min})/P_{T\,\text{avg}}$ steady-state distortions of comparable magnitude.

IV. Frequency and Amplitude Control

For engine stability test flexibility, as well as for evaluation of possible nonlinear reductions in engine surge pressure ratio as a function of peak to peak pressure amplitude, it is most desirable that such discrete frequency distortion generators have a reasonable and controllable range of amplitude output at constant frequency. Figure 6 illustrates typical Model I results at 500 Hz. The variable R-T-S spacing permits a controlled reduction in peak to peak pressure amplitude to be achieved as R-T-S spacing is increased.

Output frequency control is of course determined by the ability to maintain constant rotor RPM at the selected operating conditions and is not an aerodynamic problem. Use of appropriate electronics permitted full scale P^3G RPM control generally to within ±0.1% of nominal over most of the operating range.

Shown in the lower left corner of Fig. 4 are the operator's consoles for the 75 hp drive motor and the three stator axial positioning syncronous motors (P^3G output frequency and amplitude controls, respectively).

V. Waveform Characteristics

To simplify analytical math modelling it is desirable that the resultant pressure waveform can be reasonably represented by an analytical function. For enhancing the interpretation of experimental results on engine surge pressure ratio loss, it is desirable that frequency components of the resulting waveform not have significant amplitude compared to the fundamental. This is a tough order to fill for an installed discrete frequency generator device wherein multiple wave interactions are the rule rather than the exception.

Wave shape produced by the P^3G is affected by frequency, downstream conditions, Mach number, R-T-S spacing, and rotor/stator hole shape.

The technique used to assess waveform quality was measurement of the convergence rate of the Fourier series that represented each of the analyzed waveforms. From

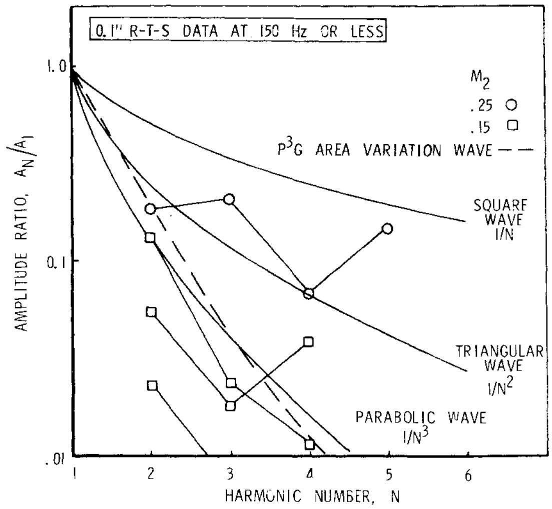

Fig. 7 Wave shape quality—spectral amplitude ratio as a function of harmonic number.

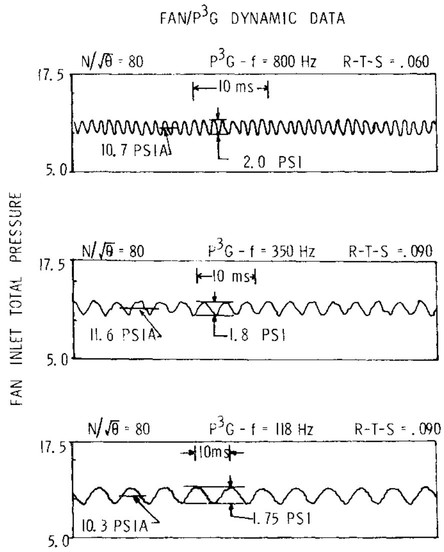

Fig. 8 Waveforms of full scale P³G with fan.

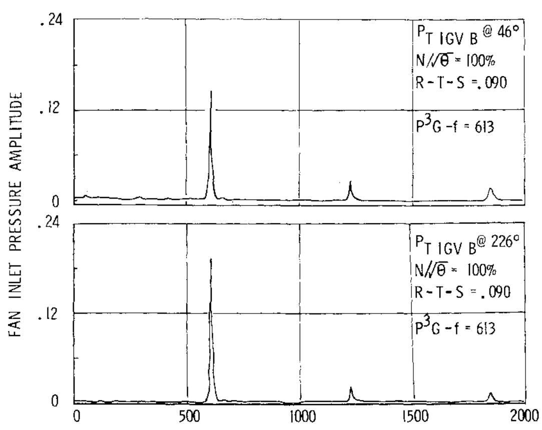

Fig. 9 Spectrum analyses.

spectra for each waveform, the amplitude of the harmonics were determined and then normalized by the fundamental or first harmonic amplitude. Typical results are plotted in Fig. 7 as a function of harmonic number. Superimposed on the grid are calculated results for 3 simple analytical waveform functions. In general, a more sinusoidal waveform (visually similar to the parabolic waveform) was produced at the lower duct Mach numbers and for

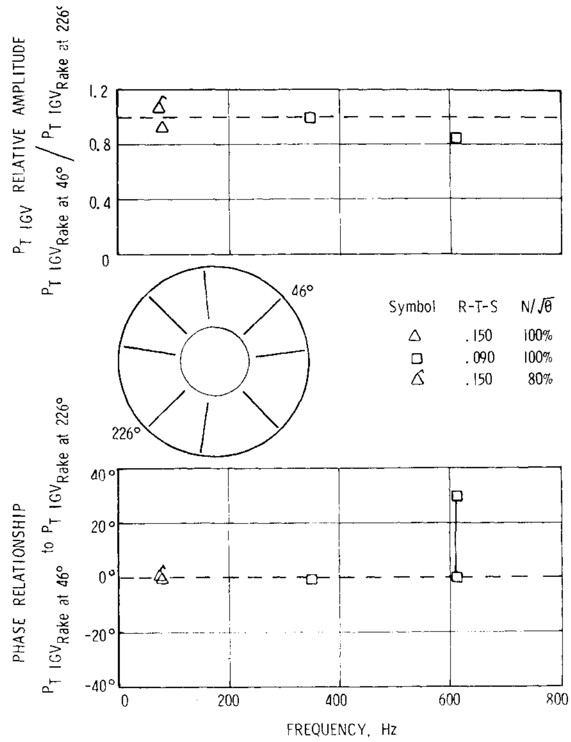

Fig. 10 Wave planarity—circumferential mode.

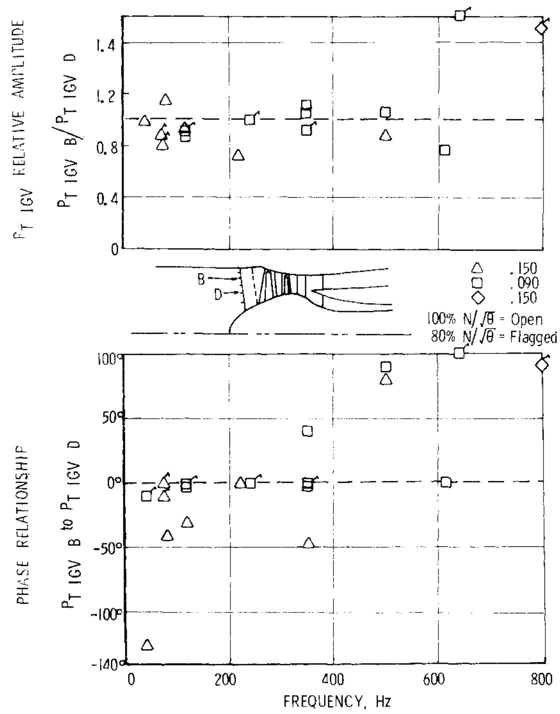

Fig. 11 Wave planarity—radial mode.

frequencies of 150 Hz or less. As duct Mach number and frequency were increased higher harmonic amplitude resulted. Over a wide range of Model I operating conditions, the amplitude of the largest harmonic was very rarely more than 50% of the fundamental and generally was less than 20%.

A subjective evaluation of waveform quality can be made from the strip chart recording of full scale P³G data obtained during fan operation as presented in Fig. 8 and substantiated by the two Fourier analyses (spectra) as Fig. 9. On this basis, the waveforms are seen to be reasonably sinusoidal and of good single discrete frequency content.

VI. Wave Planarity

Steady-state distortion levels produced during full scale P^3G operation as evaluated in terms of IDC (circumferential) and IDR (radial) distortion parameters were generally less 0.02 and nominally 0.01 or less as previously realized in the model test.

Figure 10 summarizes the circumferential planarity in terms of phase and amplitude. The probe readings from two of the rakes, 180° apart, at the engine IGV plane were averaged to obtain these summary results. Such a comparison indicates excellent circumferential planarity over the complete range of the test data.

A similar summary of radial planarity characteristics is presented in Fig. 11. In this case, all the probe readings from 2 selected radial immersions were averaged. Radial immersion B is the tip and D is the hub ring. The hub ring probes had the most deviation from those in any of the other rings, thus the results of Fig. 11 represent the "worst case."

VII. Conclusions

It has been shown that the P^3G (Planar Pressure Pulse Generator) a new dynamic distortion generator, has produced discrete frequency pressure waveforms of high quality which are controllable in both amplitude and frequency. This has been accomplished over a wider range of amplitude, frequency and airflow than reported in the literature for other discrete frequency distortion devices.

Application of P^3G type devices in component and engine stability testing should permit:

1) More comprehensive experimental isolation and study of unsteady aerodynamic instability phenomena than previously possible.

2) Establishment of a data base for validation of high speed turbine machinery dynamic math models at the higher frequencies of recent concern.

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Evaluation of Hypermixing for Thrust Augmenting Ejectors

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The additional thrust required to give an aircraft VSTOL capability may be obtained by diverting the exhaust of the cruise engine through a thrust augmenting ejector. The hypermixing nozzle has been developed to increase the rate of jet mixing and thereby improve the performance of the ejector. Since this is achieved at some cost in primary thrust efficiency, comparison tests were performed with a single shroud and three interchangeable nozzles. A one-dimensional analysis is used to compute ideal levels of augmentation and assess the relative importance of the injection losses. It is seen that hypermixing significantly improves ejector performance by making efficient diffusion of the mixed flow possible.

Nomenclature

A = area
c_p = specific heat at constant pressure
c_v = specific heat at constant volume
$\dot{m}$ = rate of mass flow
n = transfer efficiency of the mixing process
P = fluid pressure
T = fluid temperature
V = flow velocity
β = measure of profile curvature
η = nozzle thrust efficiency
ρ = fluid density
ϕ = thrust augmentation ratio

Subscripts

$_0$ = ejector inlet condition, primary flow
$_1$ = ejector inlet condition, entrained flow
$_2$ = diffuser inlet condition, mixed flow
$_3$ = diffuser exhaust condition, mixed flow
$*$ = isentropic reference condition
a = ambient condition
t = stagnation condition

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; VTOL Aircraft Design; Airbreathing Propulsion, Subsonic and Supersonic.

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Introduction

AN ejector is a mechanically simple device in which entrainment by a jet of primary fluid is used to pump a secondary flow through a duct. The thrust of the mixed flow generally exceeds that of the primary jet alone. This phenomenon can be used in aircraft applications to augment and deflect the thrust of a cruise engine in order to achieve vertical or very short takeoffs and landings. A practical VSTOL aircraft ejector has been an active research goal for several decades. However, until recently, ejectors that achieved significant levels of augmentation have been too long for aircraft installation. This was a re-