Calculated Leading-Edge Bluntness Effect on Transonic Compressor Noise

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Theme

A METHOD was developed for calculating forward-radiated shock waves and expansion regions of cylindrically blunted straight-entrance transonic compressor blades within constant-annulus inlet ducts. Tone noise at blade passing frequency and its subharmonics, caused by shock waves produced by blade curvature and nonuniformity, could be avoided in concept if all blades were precisely sharp, precisely straight, and precisely positioned. However, leading-edge thickness would necessarily be many orders of magnitude larger than the mean free path in air. Each blade, therefore, must support a detached curved wave that decays from a normal shock towards a Mach wave. It was shown by Morfey[1] that if a transonic compressor generated a periodic pressure system, the upstream asymptotic pressure field was a periodic sawtooth pattern whose strength was independent of blade shape and initial shock wave strength. This prediction has been validated analytically[2] and by numerical experiments[3] for sharp, curved blades. It was not obvious how, or if the pressure pattern generated by straight, parallel, very slightly blunted blades would approach the same amplitudes.

Contents

An earlier solution[4] had assumed that each detached shock wave had the shape of a hyperbola asymptotic to a Mach wave. In this solution, the strong inner-portion of each shock wave is approximated by a hyperbola with steeper asymptote. The hyperbola is matched to an isolated-blade weak-shock outer solution obtained from sonic boom theory[5] for blunt two-dimensional shapes. The expansion field produced by an isolated blade's leading edge is distorted by the entropy gradient downstream of the curved strong shock. Each blade's expansion field was calculated from the sonic boom solution and corrsponds to a centered expansion whose hypothetical origin is significantly downstream of the leading edge. These portions of the solution were validated by comparisons with wind-tunnel data for isolated blunt flat plates at low supersonic speeds. Compressor cascades were represented by starting with isolated-blade shock waves and expansion regions and then calculating the upstream propagation. At moderate distances ahead of the cascade leading edge plane, the variation of static pressure with distance is given by a shock-wave compression, a linear expansion to the pressure ahead of the shock, and a region of constant pressure. Eventually each blade's shock wave overtakes the aft end of the preceding blade's expansion and the pressure pattern becomes a sawtooth waveform. As upstream distance is increased, the flowfield occurring within the expansion region. That is, the Mach number just ahead of each detached leading-edge shock wave is larger than the upstream asymptotic Mach number, and the straight suction surface is at positive incidence relative to the upstream asymptotic flow direction.

Shock wave shapes calculated for a cascade of blades having leading-edge diameters 0.5% and 1.0% of the blade gap are shown in Fig. 1 for an upstream asymptotic relative Mach number of 1.40. The point at which each shock wave overtook the preceding blade's expansion fan, causing a sawtooth pressure pattern, is shown by a triangle. If the expansion fans had been approximated by straight lines from each leading edge,[6] the calculated width of the expansion region at this upstream distance would have been underestimated by about one-third. Doubling the leading-edge diameter affects only the amount by which a shock wave slope exceeds that of a Mach wave, so the actual amount of bluntness had little effect on calculated shock shape. These upstream displacements of the shock waves agree with supersonic cascade schlieren pictures.

Calculated variations of uniform-blade shock wave pressure jump with upstream distance for different bluntness at a relative Mach number of 1.20 are shown in Fig. 2. Sufficiently far beyond the strong part of the shock, pressure jump varied approximately inversely with the square root of upstream distance and directly with the square root of leading-edge diameter, as expected[5] from isolated-blade sonic boom theory. Because pressure waveform is changing with distance, calculated overall sound pressure levels decayed very slowly with upstream distance. At upstream distances of the order of the blade gap, the shock wave was bracketed by expansion regions and decayed with a strength inversely proportional to upstream distance. This change occurred at an upstream distance that varied inversely with the square root of leading-edge diameter. Thus the pressure jumps calculated for large upstream distances were roughly independent of diameter-to-gap ratio. These coalesced levels were close to the previously derived[1-3] asymptote for sharp curved blades. Pressure waveforms measured within inlet ducts for straight-entrance blades[7] validate the predicted changes of waveform shape and pressure-jump decay rate with distance.

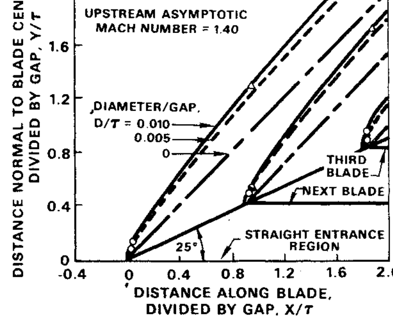

Fig. 1 Calculated effect of leading-edge bluntness on cascade shock wave shapes.

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Index categories: Aircraft Noise, Aerodynamics (including Sonic Boom); Aircraft Noise, Powerplant; Airbreathing Propulsion, Subsonic and Supersonic.

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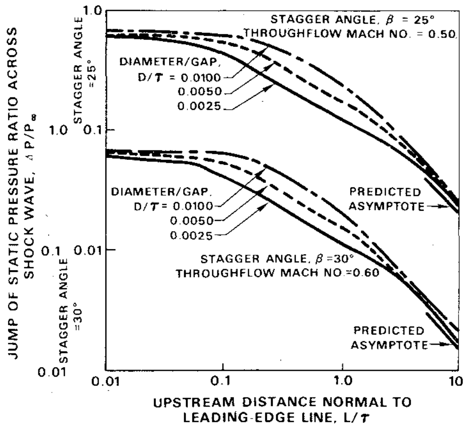

Fig. 2 Calculated shock wave pressure jump for an asymptotic Mach number of 1.20.

Attempts to reduce the tone at blade passing frequency by reducing leading-edge thickness are shown to be useless because the radiated shock strength is independent of this quantity. If reduced thickness is accompanied by increased blade-to-blade standard deviation of leading-edge thickness, then deviations in shock-wave strength and spacing would be increased, causing[3,7] an increase of multiple pure tone noise. A test rotor with very small leading-edge thickness[6] produced unusually strong multiple pure tone noise.

Effects of leading-edge bluntness on cascade performance also were calculated. Passage-averaged loss of stagnation pressure was two to three times that given by an earlier method[4] but still would be small relative to viscous losses within the blade passage. Incidence of the straight suction surface was about 2.5° for each percent diameter-to-gap ratio. Typical values of bluntness may strengthen the other half of the leading-edge shock wave, which enters the blade passage, sufficiently to cause boundary-layer separation where the shock wave is reflected from the preceding blade's aft suction surface.

Conclusions: 1) Very small but nonzero leading-edge bluntness and very small but nonzero suction surface curvature produce a farfield periodic sawtooth pressure fluctuation having a strength independent of the amount of bluntness or curvature. 2) Nonuniform bluntness of adjacent blades generates nonuniform shock wave strength and spacing, resulting in multiple pure tone noise.

References

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