Journal of Sound and Vibration 351 (2015) 119–142

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

An experimental investigation of overexpanded jets with chevrons

Brenda Henderson [a,*], Mark Wernet [b,1]

[a] NASA Glenn Research Center, MS 54-3, 21000 Brookpark Rd., Cleveland, OH 44135, USA
[b] NASA Glenn Research Center, MS 77-1, 21000 Brookpark Rd., Cleveland, OH 44135, USA

ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form
25 March 2015
Accepted 17 April 2015
Handling Editor: P. Joseph
Available online 16 May 2015

ABSTRACT

Results are presented for experiments investigating the impact of chevrons on overexpanded and subsonic jet plumes and associated acoustic radiation. Faceted, bi-conic convergent-divergent nozzles with design Mach numbers equal to 1.51 and 1.65 are used in the experiments. A design space of nine chevrons with a range of penetrations, lengths and widths are investigated. Low-penetration chevrons are shown to have limited impact on broadband and shock-associated noise for all jet Mach numbers investigated. High-penetration chevrons produce significant peak-noise reduction (relative to the baseline nozzle) in the peak-jet-noise direction with greater noise reduction for subsonic than for supersonic exhausts. High-penetration chevrons are found to increase broadband-shock-associated noise for the highest Mach number jet investigated. While particle image velocimetry results indicate chevrons introduce axial vorticity at all jet conditions, the associated mixing is limited for supersonic exhausts relative to that for subsonic exhausts due to the strong and periodic radial velocity components associated with the jet-shock-cell structure. The introduction of chevrons modifies the near-nozzle shock-cell structure and the impact of internally (within the nozzle) generated shocks on the shock-cell structure generated in the jet plume. The modifications in the near-nozzle shock-cell structure can lead to increased broadband-shock-associated-noise levels for some operating conditions.

Published by Elsevier Ltd.

1. Introduction

The application of chevrons (serrations applied to a nozzle trailing edge that protrude into the exhausting flow) to military aircraft engines for exhaust-noise reduction is particularly attractive as these devices represent a retrofit (rather than a redesign) of the nozzles and require no modifications to the engine. Extensive research on chevrons applied to subsonic jets has shown that low-frequency-noise reduction is achieved through enhanced mixing as a result of axial vorticity generated by the chevrons. However, at takeoff, tactical aircraft have engine exhausts that typically are overexpanded so previous research focused on the application of chevrons to subsonic jets is not directly applicable as the presence of shocks within the jet plume is expected to impact mixing. The present study is an experimental investigation of the noise and flow-field characteristics resulting from the

* Corresponding author. Tel.: +1 216 433 8025.
E-mail addresses: brenda.s.henderson@nasa.gov (B. Henderson), mark.p.wernet@nasa.gov (M. Wernet).
[1] Tel.: +1 216 433 3752.

http://dx.doi.org/10.1016/j.jsv.2015.04.020
0022-460X/Published by Elsevier Ltd.

application of chevrons to subsonic and overexpanded supersonic heated jets. Far-field acoustic and Particle Image Velocimetry (PIV) measurements are used to determine the impact of chevron design on the resulting jet plume and noise radiation.

Jets issuing from convergent–divergent nozzles produce exhaust conditions that fall into one of four flow regimes [1]: (1) ideally expanded supersonic, (2) underexpanded supersonic, (3) overexpanded supersonic, and (4) subsonic. For subsonic and ideally expanded supersonic jets, the flow exhausts the nozzle at a pressure equal to that of the ambient pressure and the jet is shock free. Shock-free supersonic flows are difficult (or impossible) to achieve with realistic nozzles designs (see Section 2). Underexpanded jets are the result of a stagnation pressure that is greater than that required for ideal expansion and, as a result, the flow exits the nozzle with a pressure greater than that of the ambient. A Prandtl–Meyer expansion fan forms at the nozzle lip which returns the jet pressure to the ambient pressure and turns the flow outward (resulting in an increased effective-jet diameter relative to that for ideal expansion). The expansion waves reflect from the constant pressure boundary as compression/shock waves and nearly return the flow conditions to those at the nozzle exit by the end of the first shock cell. A quasi-periodic shock-cell structure ensues. Overexpanded jets occur when the jet stagnation pressure is below that for ideal expansion but greater than that which results in the formation of a normal shock in the divergent section of the nozzle. The jet pressure at the nozzle exit is below the ambient pressure which results in the formation of an oblique shock at the nozzle lip. The shock turns the flow inward producing a decreased effective-jet diameter (relative to that for ideal expansion). As in the case of the underexpanded jet, a quasi-periodic shock-cell structure ensues. The near-nozzle flow angle and shock structure is expected to impact the acoustic performance of chevrons as chevrons introduce flow angles and pressure gradients that are generally different from those of the free jet.

Jet-noise radiation, while somewhat dependent on flow regime, is believed to be generally composed of components associated with fine-scale turbulence [2], large-scale coherent jet-structures [2], broadband shock associated noise [3–5], and screech [6]. Acoustic radiation associated with fine-scale turbulence (which contributes to acoustic radiation at small angles to the inlet axis) and large-scale coherent structures (which contribute to acoustic radiation at large angles, i.e., in the peak jet-noise direction downstream of the nozzle exit) occur for both subsonic and supersonic jets [7]. However, noise radiation from large-scale structures increases with increasing convective Mach number (and, therefore, jet velocity) and dominates the peak noise radiation when the structure phase speed (relative to the ambient speed of sound) becomes supersonic [8]. Broadband shock-associated noise (BBSN) results from the constructive interference of sound waves produced by the interaction of flow disturbances with the quasi-periodic shock structure in non-ideally expanded jets and can dominate the spectra at small angles to the inlet axis. Screech tones (part of a feedback phenomenon) are commonly produced by non-ideally expanded, cold, supersonic jets but are generally not observed in heated jets and are not present in the investigations reported here. The impact of chevrons on BBSN and noise associated with large-scale structures is the focus of the present work.

Significant understanding of the flow and noise modifications associated with chevrons has been gained through early research with tabs (nozzle inserts that protrude into the flow). Tabs have taken the general form of rectangular inserts that deflect perpendicularly to the jet axis as well as triangular shapes where the bases are mounted on the nozzle trailing edge and the apices tilted at various angles to the jet axis – a configuration closely related to the less aggressive (in terms of flow penetration and jet-plume modifications) chevron. Early investigations highlighted the significant mixing enhancement (reduction of potential core length) and entrainment resulting from the application of tabs to subsonic jets [9]. In supersonic jets, tabs produce similar mixing enhancement benefits to those in subsonic jets and modify (typically reduce) shock cell lengths [10]. Mixing enhancement results from vorticity generated through two processes: (1) the adverse pressure gradient formed upstream of the tab as a result of the reduced velocity of the approach flow and (2) vorticity shed from the tab edges as a result of the pressure gradient across the tab surface which reorients in the streamwise direction with downstream distance [11]. As a result of the second vorticity generation process, triangular tabs with apices tiled in the flow direction (a design characteristic of all chevrons) produce enhanced plume mixing relative to those protruding normal to the jet axis or tilted in the upstream direction as the vortex filament starts with a favorable inclination and augments the vorticity generated by the first vorticity generation process. The resulting counter-rotating vortices generated by each tab through mutual induction cause the vortex pairs to initially move towards the jet centerline then move radially outward as the neighboring vortex pairs approach each other. The outward radial motion of the vortices causes the significant lateral spreading of the jet [12]. In supersonic jets, tabs eliminate screech tones [10] and can (for favorable geometries) reduce low frequency noise while increasing high frequency noise in the peak jet-noise direction [13]. Screech tones are eliminated through alteration of the shock-cell structure. Low-frequency-noise reduction is achieved through enhanced mixing which alters the growth of the jet shear layer and reduces the spatial extent of high-velocity flow.

Early work with chevrons focused on applications to separate-flow, dual-stream, subsonic jets. Chevrons typically have far less flow penetration and, therefore, generate lower vorticity levels than tabs. Initial studies showed the significance of chevron count, jet mixing velocity (obtained from a mass-weighted average of the core and bypass stream velocities), and chevron location (fan or core stream) on the resulting acoustic spectra [14]. Noise reduction was found to decrease with decreasing mixed velocity, presumably due to the reduced velocity difference between neighboring jet streams which reduced the impact of the mixing devices on the plume evolution. Fan chevrons were found to increase high-frequency noise in the peak jet-noise direction possibly due to the influence of the fan stream on noise radiated from regions of the flow near the nozzle (a result consistent with single-stream chevron experiments [15]). Later studies showed that chevron count had far less impact on acoustic radiation than chevron penetration (with increased penetration having increased low-frequency noise-reduction benefits) [16]. Additionally, a connection between chevron penetration and velocity difference was observed in the high-frequency-radiation characteristics of the jet (an indication that one-variable-at-a-time experiments may not adequately quantify the connection between chevron geometry and resulting acoustic radiation). Particle image velocimetry (PIV) measurements highlighted the enhanced mixing as well as reduced