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Influence of nozzle spacing and diameter on acoustic radiation from supersonic jets in closely spaced arrays

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Acoustic emissions were characterized for fourteen, 8 × 8 arrays of axisymmetric supersonic jets experimentally. The nozzle diameters ranged from 3.2 mm (1/8 in.) to 6.4 mm (1/4 in.) and the hole-to-hole spacing (S) over hole diameter (d), or the S/d ratios ranged from 1.44 to 3. The arrays were tested at several net pressure ratios ranging from 2 to 24. It was found that up to a critical net pressure ratio, the arrays radiated ultrasonic frequencies. Beyond this critical net pressure ratio the characteristic frequency decreased to lie within the audible range. Frequency response plots of the sound pressure indicate a broadband frequency peak generated by the turbulent mixing noise of the jet. At lower net pressure ratio (NPR) values, this broadband peak is similar to a single jet within the jet array. However, as the NPR continues to increase this frequency peak shifts to lower values which are similar to a single jet with an equivalent exit area of the entire array. Dimensional analysis revealed that at a critical net pressure ratio a dramatic reduction in the characteristic Strouhal number occurred. A small increase in the characteristic acoustic pressure was also observed at net pressure ratios below the critical net pressure ratio and a larger increase was observed at higher net pressure ratios. The critical net pressure ratio appeared to be a linear function of S/d for the nozzle arrays. A linear curve fit was applied to the measured critical net pressure ratio and this was compared to a theoretical model prediction. The experimental results revealed that the critical net pressure ratio is well predicted by the models.

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1. Introduction

Radiated noise from supersonic jets is an area of significant research interest. The focus of this research is to better understand and characterize the acoustic emissions from arrays of multiple supersonic jets and in particular the relationship between jet diameter, nozzle spacing, and net pressure ratio (NPR) to acoustic radiation.

Methods to predict acoustic loads from supersonic jets are needed to improve the design process. Models derived by Carucci and Mueller [1], and Eisinger [2] predict acoustic loads caused by high pressure gases in piping networks based upon thermodynamic and physical parameters upstream of the flow. Although these models are used as a standard they have a limited pressure drop range. Experimental testing with a much larger pressure drop range is vital to better understanding the acoustic radiation and flow characteristics.

Methods to reduce the acoustic radiation from jets are also important design needs. For example, Carucci and Mueller [1] suggest that acoustic emissions may be reduced by implementing Venturi slots within a valve to divide a single larger flow into several smaller parallel plane jets. Furthermore, Raman [3] showed that two rectangular jets spaced closely together will eliminate the effects of screech. More recently, research into jet arrays comprised of two and four circular nozzles has been performed by Umeda and Ishii [4,5]. They revealed how the frequency of screech produced by multi-jet arrays was altered with respect to an increasing pressure ratio.

This research investigates the overall noise emitted from supersonic jet arrays which includes all noise sources such as turbulent mixing noise and screech. This work does not focus only on screech tones as some work has done. Critical to this research and analysis is a discovery by Seiner et al., [6] who determined that the Strouhal number (St) emitted from supersonic jets is approximately 0.2. The Strouhal number is a dimensionless parameter and in this work is defined as the acoustic frequency, f, times the fully expanded jet diameter, d, over the velocity of the fully expanded jet, u, as shown in Eq. (1). The subscript j represents the fully expanded point which for an under-expanded supersonic jet occurs just outside and downstream of the nozzle where the jet expands to its greatest

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cross sectional area. The greatest jet velocity is also found at this point for under-expanded jets.

$$St = \frac{f \cdot d_j}{u_j} \quad (1)$$

Previous research has shown that the turbulent mixing noise of a jet has a very wide, broadband frequency peak. In this work this peak will be termed the characteristic frequency and should not be confused with the narrowband spikes often due to screech. A principal aim of this paper is to describe how the characteristic frequency (or frequencies) present in supersonic jet arrays are effected by diameter size and nozzle spacing. This has implications regarding the frequency content of the acoustic radiation and the resulting acoustic loading. For example, an increase in characteristic frequency is obtained by decreasing the fully expanded diameter of a single jet [6]. Thus, multiple small jets with ultrasonic characteristic frequencies might be advantageous to a single larger jet of equivalent area with characteristic frequencies in the audible range. However, there are multi-jet effects that merit consideration. Kandula [7] has shown that the power spectra from closely spaced rockets reveal two peaks; the higher frequency peak represents the acoustic emissions from each individual rocket nozzle, and the lower-frequency peak is caused by the radiation from the combined jet stream of the multiple rockets.

In this work the NPR is defined as the supply pressure of the supersonic jet over the pressure of the medium the jets are exhausted into; the medium in this case being the atmosphere. Recent research [8] showed that in jet arrays three basic shock structures develop as a function of the NPR. The first region consists of completely separate, unmerged shock cells. The second region consists of an oscillatory shock lattice and in the third region a stable merged shock cell lattice forms. It was shown that the overall sound pressure level (OASPL) also transitions between these stages. In the first stage the OASPL for the array is similar to a single jet and increases as the NPR increases. In the second stage the jet arrays no longer compare to a single jet. The OASPL is higher and increases at a much slower rate as the NPR is increased. In the third stage the OASPL levels off and does not continue to increase with NPR. It was also shown in this work that the NPR values where the different shock developments exist is a strong function of the jet diameter and jet spacing.

This paper builds on these findings and makes the following contributions

1. A specific NPR for each jet array exists where the radiated noise drops from the ultrasonic region to the audible frequency range. This NPR is called the critical NPR and appears to be a linear function of the spacing over diameter ratio of the jet arrays.
2. Frequency analysis of a large range of experimental data is presented. The data indicate that the turbulent mixing noise of the jets is a function of the jet spacing to diameter ratio and the NPR. A shift from high to low frequency occurs at increased NPR values for increased jet spacing to diameter ratio. The difference in frequency spectra between single jets and jet arrays is also presented and discussed.
3. Dimensional analysis reveals that a dramatic reduction in the Strouhal number also occurs at the critical NPR. It is shown with dimensional analysis of the acoustic pressure spectra along with thermodynamic flow parameters that a dramatic shift in the broadband turbulent mixing noise peak occurs when the shock cells begin to interact.
4. A predictive model based on the jet diameter and spacing is developed that can be used to predict the critical NPR. The model is based on experimental data and compared to analytical results for validation.

This paper builds on previously published research [8] and therefore first briefly summarizes the previous work. The paper then describes the spectral, dimensional, and other analyses that lead to the above listed findings.

2. Summary of prior results

The research presented in this paper extends a recent investigation performed by the authors [8], in which the OASPLs were characterized and correlated with the fluid shock-wave structures within the flow of closely spaced supersonic jet arrays. In particular, two principal findings from the prior study are briefly reviewed. They involve the establishment of three distinct flow regimes generated by the jet arrays. The flow regime and OASPL were found to be functions of the center-to-center spacing of the nozzles, S, over the nozzle diameter, d, or (S/d) and the NPR. The merging of supersonic jets alters the OASPL emitted from the supersonic jet arrays. At NPR values below the point of merging, the OASPL is similar to that of individual jets within the jet arrays. As the jets merge they first form an oscillatory shock lattice, and then a stable shock lattice at higher NPR values. The OASPL increases by approximately 40 dB throughout the range of NPR investigated. This section was to provide a review of the research that this paper now builds on and continues to investigate.

3. Test setup and data acquisition

The facility used to produce the wide range of NPR values was a high pressure blow down facility that has a maximum capacity of 11.0 MPa and a total volume of 24.1 m^3. Flow was released through a control valve which controls the air flow passing through the array. Just downstream of the control valve is 15.2 cm (6 in.) schedule 80 pipe that expands to 20.3 cm (8 in.) schedule 80 pipe.

The supersonic jet arrays are all arrays of 8×8 jets made by drilling holes in flat steel plates and attached to the exit of the letdown facility as shown in Fig. 1. The center-to-center distance between jets is the same in both the horizontal and vertical directions. The nozzle diameters investigated ranged from 3.2 mm (1/8 in.) to 6.4 mm (1/4 in.). The center-to-center spacing over the nozzle diameter (S/d) ratios investigated ranged from 1.44 to 3.

Static pressure measurements were acquired with an Omega PX309-500G5V pressure transducer and differential pressure measurements were acquired with a pitot tube and an Omega PX409-015WU5V. The NPR values investigated ranged between 2 and 24. This ratio is defined as the static pressure of the flow, acquired

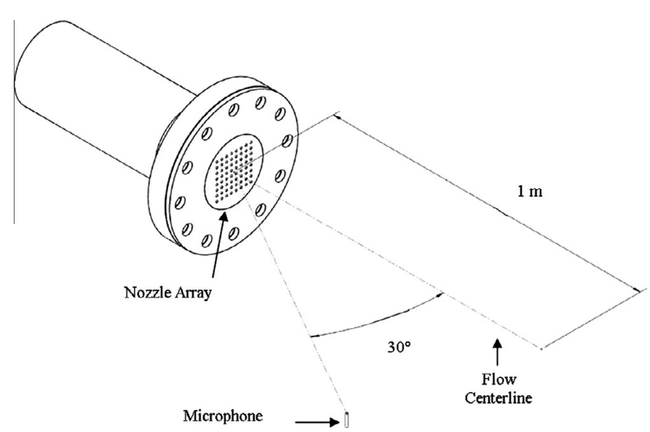

Fig. 1. Schematic of jet array, microphone placement, and connection to the blow down pipe.

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