Jet flow instability and its role in the mechanism of sound generation

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The present paper addresses the compressible unsteady flow in supersonic underexpanded jets. This flow is typically accompanied by rather strong noise that results from a complicated flow structure downstream the nozzle exit. It basically includes flow features such as shocks, vortices, laminar-turbulent transition, and eventually the formation of a turbulent plume. Aeroacoustics of jet flows is knotted: the questions like "where are basic noise sources located" or "which mechanism is responsible for one or another type of sound produced by the jet" are still far from their ultimate answers.

This study concerns one, but important aspect of jet aeroacoustics that is known in literature as jet screech. This phenomenon is typically appears in supersonic underexpanded jets as strong sound at a discrete frequency. Its amplitude can amount up to 40-50% higher than the amplitude of the broadband noise.

Due to A. Powell a theory of the jet screech exists that explains appearance of this sound as the result of the interaction between roll-up vortices at the jet boundary and shock-cell structures [1]. However, our recent numerical studies of the jet flow points at the presence of strong correlation between jet screech and helical instability [2]. This allows us to set forward a new hypothesis concerning the jet screech mechanism.

In accordance with this hypothesis the screech sound is due to helical instability that may develop in the jet flow under certain conditions. Because of this instability the flow pattern is drastically changed. An asymmetry appears, and the jet takes a typical spiral shape. The jet core begin to behave like a gaseous drill that quickly rotates in the ambient gas generating strong tonal sound. The frequency of this rotation is found to closely correlate with the screech frequency.

Supposing that the helical instability is an inherent feature of any jet flow we choose a simple model of the jet flow that in somehow approximates the real one and subject it to the linear-stability analysis. In this way we can educe helical unstable modes and calculate their frequency characteristics under different flow regimes. The data obtained we then compare with experimental data obtained in Nagoya University, Department of Aerospace Engineering, Fluid Dynamics Lab (Prof. Y. Nakamura).

The base flow to be investigated with the linear-stability analysis is axisymmetric. Flow parameters depend on radius only. The velocity profile is taken in the form $U(r) = 0.5U_j\ 1+\tanh\left[\theta\ R/r - r/R\ \right]$, where U_j is the core velocity, θ is a variable parameter that controls the width of the shear layer near the jet boundary. Pressure is constant. The temperature profile is related to the velocity by means of Busemann-Crocco law which is valid for a boundary layer flow with a Prandtl number *Pr=1*. The density is then defined through the equation of state.

The core parameters correspond those of the perfectly expanded jet, and are defined by $NPR = P_0 / P_a$, where "0" and "a" mean total and ambient, respectively. Thus, only 2 control parameters , NPR and θ, characterize the model jet flow under consideration.

The disturbances are investigated in the form of normal harmonics $\exp i\ \lambda t + kx + m\varphi$, where the longitudinal wave number and the integer azimuthal wave number are real, while $\lambda = \lambda_r + i\lambda_i$ to be determined is generally complex. λ_r is the radian frequency, and $-\lambda_i > 0$ is the temporal growth rate.

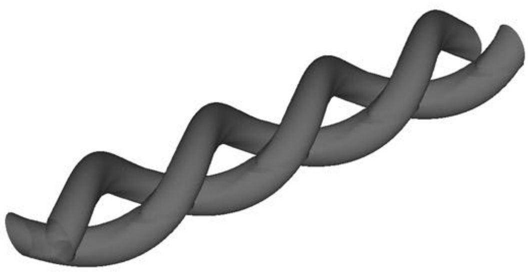

Fig. 1. Spiral Shape of pressure disturbances for the *m=2* mode.

Basic results of the linear analysis are as follows.

1) Unstable modes come out in the form of a slender vortical tube that spirally surrounds the jet core. In Fig. 1 we show isosurface of the pressure disturbance for the m=2 mode. Developing in time these two tubes form a typical spiral structure.

2) There is a value of the wavenumber K that corresponds the most unstable mode. Fig. 2 shows $-\lambda_i$ as a function of K for different NPR and the mode $m=2$. This implies that the spiral instability should develop at a certain longitudinal wave length.

3) The frequency of the most unstable mode shows almost linear increase with increasing θ that controls the width of the velocity profile, as can be seen in Fig. 3 where the frequency in Hz is shown vs θ.

4) Fig. 4 displays the most unstable frequency depending on *NPR*. As can be seen, the frequency is increased as *NPR* decreases. Also the above mentioned experimental data is shown. These data match theoretical predictions of θ.

This supports our main conclusion that the screech phenomenon is the result of the helical instability that develops in the jet flow changing it into a spiral drill-like structure. And that the screech sound closely resembles the sound producing by a quickly rotating in air drill.

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[1] Powell, A. 1953. On the mechanism of chocked jet noise. Proc. Phy. Soc., B66, p. 1039.

[2] Menshov, I., Semenov, I. & Ahmedianov, I. 2008. Mechanism of Discrete Tone Generation in Supersonic Jet Flows. *Doklady Physics*, 53, No 5, p. 278-282.

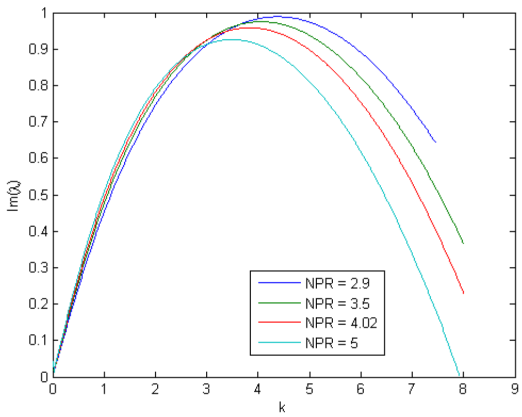

Fig. 2. The growth rate vs K at different *NPR* and θ *=6.25.*

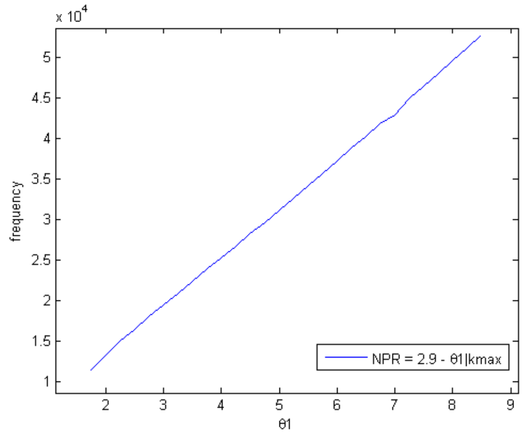

Fig. 3. Frequency of the most unstable mode vs $\tilde{\theta}$

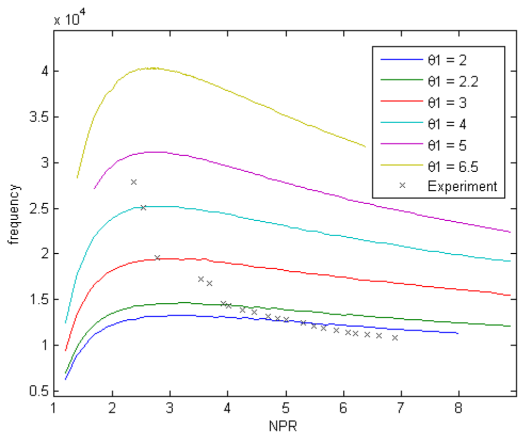

Fig. 4. The most unstable mode frequency vs *NPR*; the markers indicate experimental data.