Investigation of acoustic and gas dynamic characteristics of strongly swirled turbulent jets

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Abstract. Generalization of the series of experimental and numerical results for properties and characteristics of swirling jets with high swirling intensity $W_0 > 1$ is considered. These jets are typically used in gas turbine aviation engines for intensification of mixing process and combustion process stabilization. Flow structures in swirling jets and in the near-field are analyzed. It is shown, that, in the main, the flow structure behind the swirling device can be determined by swirling intensity $W_0$ and acoustic fluctuations field formed far from the jet boundaries. Experimental measurements and numerical simulation of the noise levels of the highly swirling jet are performed using Ffowcs-Williams-Hawkins analogy. Maximum levels of noise axis are observed at angles of 50°-70° from the jet.

1. Introduction

Most of the modern turbojet aviation engine combustors use swirling flows after frontal devices to intensify mixing, however, a number of mechanisms in such flows are not fully clarified yet, including conditions and mechanisms of the secondary loss of the swirling jet stability. Investigations of swirling turbulent jets show that a swirling jet generates intensive acoustic radiation in the form of discrete tones, when swirling intensity is more than one. The swirling jet generates a tone noise while the noise of the non-swirling turbulent jet appears to be broadband. Thus, swirling jets are a suitable object for acoustic field investigation, because pressure and velocity pulsations spectra of swirling jets have marked frequencies.

The flow behavior in swirling jets is determined by two main parameters: Reynolds number and swirling intensity $S$, which correlate axial and circumferential angular momentum fluxes [1]:

$$S = \left( \frac{2}{3} \int_0^\infty \rho U_x U_r r^2 dr \right) \left( \frac{D}{2} \int_0^\infty \rho \left( U_x^2 - \frac{U_r^2}{2} \right) r dr \right)^{-\frac{1}{2}}.$$

Here $\rho$ is the density, $U_x$, $U_r$ are the axial and rotational velocity components, $r$ is the radial coordinate, and $D$ is the diameter of the swirling device outlet cross-section. The magnitude of swirling intensity defined this way remains constant in axial direction due to the momentum conservation law.

Commonly, the swirling magnitude defined as $W_0 = \frac{U_{r,max}}{U_{r,avg}}$ [2] appears to be more useful for measurements and calculations; here $U_{r,max}$ is the maximal circumferential velocity in the current section, and $U_{r,avg}$ is the mass flow averaged velocity in the section. It can be shown that $W_0 \sim S$. In practice, the swirling jet is created in primary combustor zone by means of different types of swirlers.
with a swirling intensity within the range of $W_0=1.1\text{-}1.8$. These swirling magnitudes correspond to stable reverse flow zone.

2. **Flow structure in highly swirling jet behind the swirling device**

Detailed investigations of flow structure in the swirling jet are performed in [2-5]. The scheme of highly swirling jet in fig.1 may be used as a generalization of these results; here the instantaneous axial velocity field for the swirling jet with $W_0=1.36$ in submerged space is presented as well. The flow structure consists of reverse flow zone (RFZ) (1) located near the axis of the device, the zone of mixing layers (2) and ambient ejection zone (3). Other above mentioned investigations prove the presence of linear relation between the average dimensionless length of reverse flow zone and the swirling intensity in the form of [2]:

$$L^* = L / D = 4W_0.$$

(1)

Here $L$ is the dimensionless reverse flow zone length, and $D$ is the diameter of the swirling device outlet cross-section. Computational and experimental data for $L^*$ for different swirling devices, such as atomizers and blade swirlers, are presented in figure 2. Experimental data were obtained by Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) techniques, and computational results were obtained by numerical solution of Navier-Stokes equations. Details of measurement technique and experimental facility can be found in [6, 7], details of computational procedure in [8]. Dashed line in figure 2 shows dependence (1). Figure 2 demonstrates that RFZ exists in the flow at $W_0>0.7\ldots0.8$, and it appears to be unstable at $W_0\sim1$ regimes, i.e. small perturbations may lead to its complete disappearance. In the range of $2.5\sim W_0 \sim 1$ the back-coupling mechanism [4] stabilizes RFZ, and it can exist in the average flow even in the presence of large upstream perturbations. At $W_0>2.5$ the swirling jet “breaks up”: spiral vortex structures in the flow lose integrity and break into separate large-scale vortexes, which come off from the edge of the swirling device nozzle; and jet loses its periodical motion structure.

![Figure 1. Typical flow scheme in highly swirling jet. Contours - instantaneous axial velocity, numbers: 1 - reverse flow zone, 2 - mixing layers, 3 - ambient ejection zone, white vertical line - nozzle exit. Numerical results.](image1)

![Figure 2. Dimensionless reverse flow zone length for different swirling devices. Measured and calculated values.](image2)
Here $b_j$ are the parameters, and $N_1$ and $N_2$ parameters define thicknesses of the inner and outer mixing layers. Such representation of the averaged flow allows applying linear stability analysis of averaged flow field relative to small perturbations [11, 12]. Stability analysis and data obtained in the experiment and from numerical solution of filtered Navier-Stokes equations show that complicated precessional motion of RFZ exists in a jet with $W_0 > 1$, and this motion appears to be a source of a tone noise. Thus static pressure pulsation spectra in the far-field have a distinct tone, which contains the major part of total acoustic energy radiated by jet (more than 80%).

3. Swirling jet noise

Unsteady flows in highly swirling jets produce acoustic fluctuations outside the jet. In this research, the acoustic field and flow characteristics outside the jet are experimentally measured using microphones and constant temperature anemometry techniques. Computational results are based on numerical solution of unsteady three-dimensional filtered Navier-Stokes equations, using the control volume method and well-known SIMPLEC [13] procedure, reformulated for compressible flows. Precessional motion in the jet with high swirling intensity produces mass flow rate fluctuations in ejected medium (zone 3 in figure 1), however pressure and velocity fluctuations do not correspond to the properties of acoustic disturbances. Numerous studies conducted for different swirling devices, such as atomizers and blade swirlers [2, 3], including current research, show, that for jets with $W_0 > 1$ the frequency of the first harmonic ($f_0$) of a distinct tone can be connected with swirling intensity in the following way:

$$ Sh = f_0 D / U_{x,avg} \approx 0.7 W_0. $$

This frequency coincides with hydrodynamic frequency of RFZ rotation about the symmetry axis of the swirling device. It is also possible to observe the second harmonic of distinct tone in the spectra of pressure and velocity fluctuations; it arises from asymmetry of RFZ form in cross section. Experimental and numerical data for the first harmonic of natural frequency of swirling jets, flowing from different swirling devices, are presented in figure 3. The dashed line in figure 3 indicates the dependence (2) with sufficient accuracy reproducing the calculated and experimental data both for blade swirlers and for centrifugal atomizers [14]. Separate points for blade swirler type devices with predominating second harmonic in the spectrum are given in figure 3 ($2f_0$, marked by triangles). There are two frequencies with prominent amplitude in pressure and velocity fluctuations spectra for such devices. Existence of the distinct tone in highly swirling jet allows studying the acoustic disturbances formation in the far-field by measurements and calculations only for the frequency of the first harmonic. Transition from convective type disturbances in the jet and in the near-field to acoustic disturbances are illustrated in figure 4. Figure 4 shows static pressure fluctuations intensity for the first harmonic frequency for two-stage blade swirler (with vortex tube) at different distances from the swirling jet source along the radius with angle of 60° to symmetry axis. Experimental and numerical points are denoted by square and circle markers, respectively, and the dashed line indicates theoretical relation between the amplitude and the distance for acoustic disturbances. As can be seen in figure 4 pressure fluctuations levels converge to acoustic type line at distances $R/D \approx 10$. Numerical results for $R/D \approx 20$ also lie near the theoretical dependence.
To describe swirling jet formation and propagation processes and to investigate acoustic characteristics of highly swirling jets this work applied the numerical procedure based on detached eddy simulation approach (DES) [15]. As can be concluded from previous works, DES approach has a number of principal advantages for highly swirling jet investigations in comparison with RANS approach. One of the main advantages is the potentially more accurate description of turbulent fluctuations spectrum, and consequently, a more appropriate description of unsteady flow parameters. At the same time, simulation accuracy is determined, among others, by the width of directly resolved part of turbulent spectrum that explicitly depends on cell sizes in computational domain. Another factor, which affects the accuracy of unsteady characteristics, is the collected flow statistics; it is especially important for spectral characteristics of the flow. It has been also clarified that the main difficulty for DES approaches is the description of the flow in the transition region from the LES solution to the RANS solution, which implies the complexity of determining the universal type of limiter \( l_{DES} \). Thus, different types of limiters implicitly impose limitations on the characteristics of the computational grid in the transition region and in the boundary layer; often these restrictions explicitly depend on the characteristics of the current flow itself: the thickness of the boundary layer, the pressure drop along the boundary layer, and so on. In current research, an IDDES-type limiter (Improved Delayed DES- IDDES) was used to describe a swirling jet, taking into account the assumed values of the determining characteristics [16]:

\[
I_{IDDES} = f_d (1 + f_e) l_{RANS} + (1 - f_d) l_{LES}.
\]

Here \( f_d, f_e \) are the damper functions, and \( l_{RANS}, l_{LES} \) are the spatial scales of RANS and LES zones respectively. A more detailed description of the form of damping functions and scales can be found in [16]. A comparison of the results of IDDES calculations with experimental data on the mean and pulsation characteristics for swirling jets is presented in [17]. In addition to calculating the flow fields for determining the noise levels in the far field, the integral formulation of the Ffowcs-Williams-Hawkins method is used in current research. The scheme of the experimental model for performing acoustic measurements is shown in figure 5. The model consists of a blade swirler, a vortex tube mounted to the outlet of the swirler and a nozzle. The model creates a swirling jet with \( W_0 > 1 \). The results of measurements of pressure fluctuations levels for the presented model are shown in figure 4, and the results of calculations are in figure 4 (marked by circle) and in figure 6. Figure 6 shows the directional diagram of the noise of a swirling jet for \( R = 1 \) m, indicating that the maximum noise level
is observed for the model in question at angles of 50 ° -70 ° and this maximum has the value of 80-85 dB.

**Figure 5.** Surrounding hemisphere scheme for pressure fluctuation measurement and calculation.

**Figure 6.** Directional diagram of pressure fluctuation in the far-field of the swirling jet, R=1 m, D=44 mm

### 4. Conclusions

Numerical and experimental investigation of the properties and characteristics of submerged swirling jets with a large swirling intensity $W_0 > 1$ has been performed. On the basis of available data, the correlations between the size of the RFZ, precession frequencies of the swirling jet and swirling intensity have been generalized and analyzed. It is shown that the criterion dependences proposed in [2] can be applied not only to swirling devices such as atomizers, but also for other types of swirling devices. Based on the features of the spectrum of pressure and velocity fluctuations in highly swirling jets it is shown that acoustic pressure fluctuations are formed for a swirling jet at distances $R/D > 10$. And the maximum intensity for a typical highly swirling jet has a noise in the far-field at the angles of 50° -70° from the device axis.

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