Formation of Inverse Energy Cascade in Free Turbulent Jet

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The evidence of inverse spectral energy transfer in turbulent round jet is presented via Large Eddy Simulation with constant Smagorinsky model. Numerical simulation has been performed for wide range of Reynolds numbers and with applying low-amplitude inlet fluctuations and swirl. By varying these parameters, it has been possible to investigate the influence of different vortex stretching patterns on the amplitude and sign of spectral energy flux in the near region of the jet.

In spatially evolving turbulence there are several distinguishable stages when the flow is transiting from organized to chaotic state. One of the spectacular features of the flow, observed during this transition, is appearance of coherent structures. These coherent structures, forming in the initial zone of mixing layers, demonstrate order in their periodic formation and movement; however, it is their evolution that in the end brings the flow into chaotic, turbulent state. The rapidity of this transition may be influenced by many external conditions. Low amplitude inlet fluctuations in turbulent jets in some cases cause changing in flow vortex structure and higher moments of velocity pulsations [1]. Swirling applied to the flow may also affect the behavior of vortex energy exchange. Most likely, these changes are due to different ways of vortex interaction (stretching of vortex tubes, or vortex merging). These issues have been addressed in present study.

It is known, that increasing flow Reynolds number leads to more rapid growth of instabilities, and therefore transition to isotropic turbulence occurs sooner. In the round jet case, two-dimensional ring vortices become star-shaped and then totally lose any symmetry, becoming fully three-dimensional. Applying additional swirl to the jet forces the ring vortices to become spiral-like, due to vortex interactions this process is accompanied by additional longitudinal vortex stretching. To the contrary, inlet fluctuations at the certain frequencies appear to prolong the lifespan of ring vortices, witch gives less vortex stretching in the initial region of the flow. Therefore, by varying these three parameters – Reynolds number, inlet fluctuations and swirl – it is possible to change the amount of vortex stretching and its contribution to the net turbulence generation.

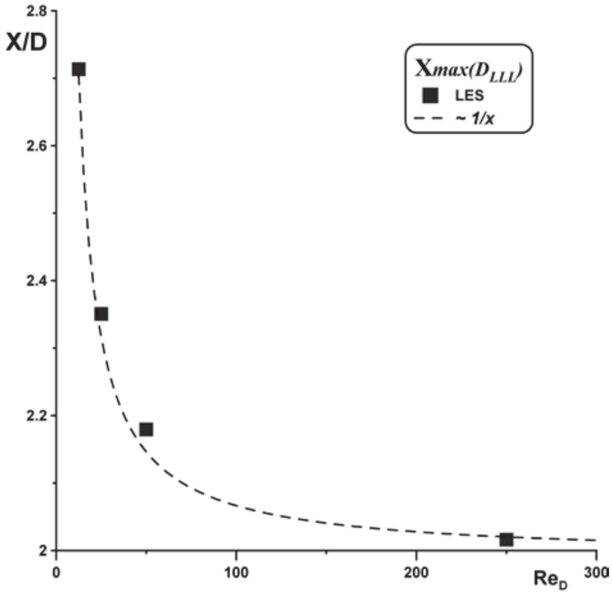

Fig.1. Longitudinal coordinate of D^*_{LLL} maximum for different *Re.*

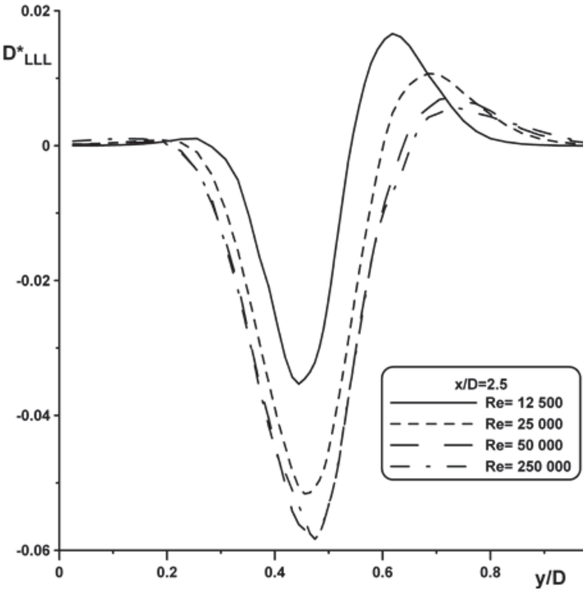

Fig.2. D^*_{LLL} distribution in radial cross-section x/D_{in}=2.5.

Results of numerical simulation

The subject of the study was submerged turbulent round jet. Details of the numerical procedure, boundary and initial conditions are described in [2]. In [2] there also present the distributions of mean and R.M.S. velocity and pressure compared with Particle image velocimetry (PIV) experiment. Numerical and experimental results show good agreement.

For detailed analysis of spectral energy flux in case of no inlet fluctuations in [3] the value of the flux was calculated directly, using energy balance equation, obtained (see [4]) by applying low-pass filter to the Navier-Stokes equation.

In LES, only spatial scales larger than grid scale are resolved directly, and sub-grid scales are modeled. In present study, we use a simple constant Smagorinsky model for that matter. Therefore, the calculated flux value does not include the sub-grid scales term. This issue was addressed in [5] where it was shown that for the scales sufficiently (5-10 times) larger than the grid scale a sub-grid energy flux may be neglected.

Simulations for different Reynolds numbers

To investigate the inverse energy flux formation several simulations were performed for Reynolds numbers $Re = U_{in} D_{in} / \nu$ in the range: 12500÷250000 (where U_{in} is mean flow rate and D_{in} is nozzle diameter). The distributions of dimensionless third order structure function of the flow $D^*_{LLL} = D_{LLL}(\ell) \Big/ \left(\ell U^3_{in} / D_{in} \right)$ (here and after l=0.05D_{in}) for all *Re* are topologically similar (see[2]), except for the amplitude of maximum, which is slowly growing with increase of Reynolds number, and the position of this maximum, which shifts towards the nozzle (see fig.1). The shift of the maximum obey approximately the hyperbolic law, with the saturation value for the D^*_{LLL} maximum coordinate x/D_{in}=2. Fig.2 shows that for all used Reynolds numbers in the near region of the jet there are positive values of D^*_{LLL} that can

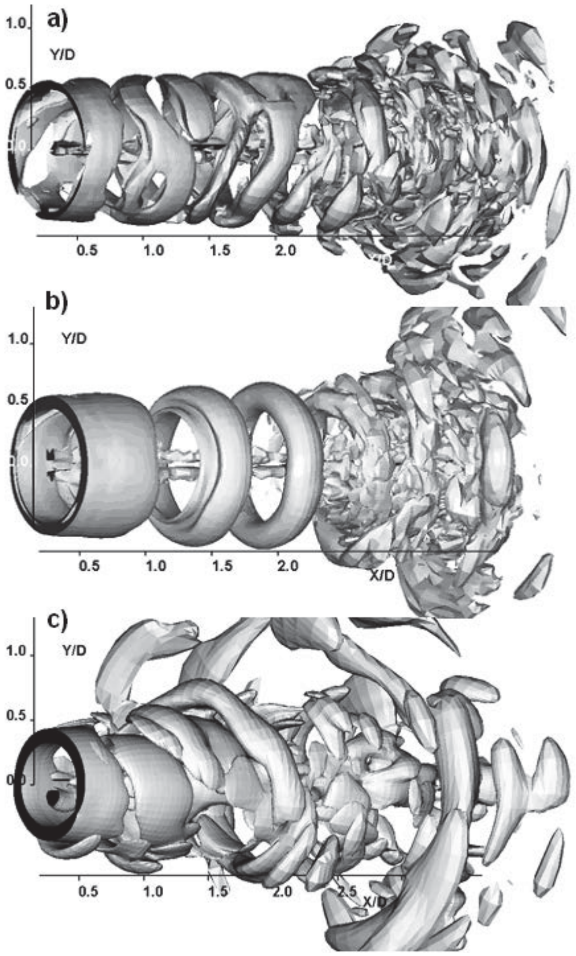

Fig.3. Vortex structure of the jet (λ_2=*-60* isosurfces). (a) no inlet fluctuations, (b) *Sh=0.75*, (c) with swirl *S=0.6*

be associated with inverse energy flux. The larger is *Re* the faster is broadening of the mixing layer, and therefore, regions with positive D^*_{LLL} are farther from the jet axis for the same x/D_{in}.

Inlet fluctuations and swirl

In the present work we investigate the effect of inlet fluctuations and swirl on the vortex structure of the jet. The range of examined Strouhal numbers $Sh = 2\pi\omega D_{in} / U_{in}$ was 0.25÷1.5, with the amplitude of fluctuations ~$0.01U_{in}$. The most prominent changes of the jet vortex structure are observed for the *Sh*=0.75 (fig.4b). The ordering property of the fluctuations is clearly evident, vortices in the initial region are strictly toroidal and transition to turbulence is more sudden than in undisturbed case. The toroidal shape of the vortices indicates that there is less vortex stretching occurring for that flow regime, and the energy transfer between vortices is caused by vortex merging (pairing) and hence the transition of energy is from smaller scales toward larger ones.

Adding swirl causes increase of vortex stretching due to change of flow topology. Axial symmetry is lost, and geometry of the vortices becomes spiral-shaped. That increase of vortex stretching cause faster transition to turbulence, which is evident in fig.3c. 3D features of the flow now grow much faster, giving base to the direct energy cascade and dissipation.

Fig.4 shows D^*_{LLL} radial distribution for different distances from the nozzle. It is evident that inlet fluctuations on the certain (resonant) frequency intensify the positive D^*_{LLL} (associated with inverse energy flux) values, and the swirl is evidently depressing this effect (D^*_{LLL} is negative for x/D_{in}=2.5 and further downstream).

Given this evidence, it is possible to say that in the initial region of the jet there are two competing processes: vortex stretching and vortex merging. Dumping one, we automatically increase the other, that give us tools to manipulate flow regime and resulting energy balance in a wide range by applying low-amplitude external action to the flow.

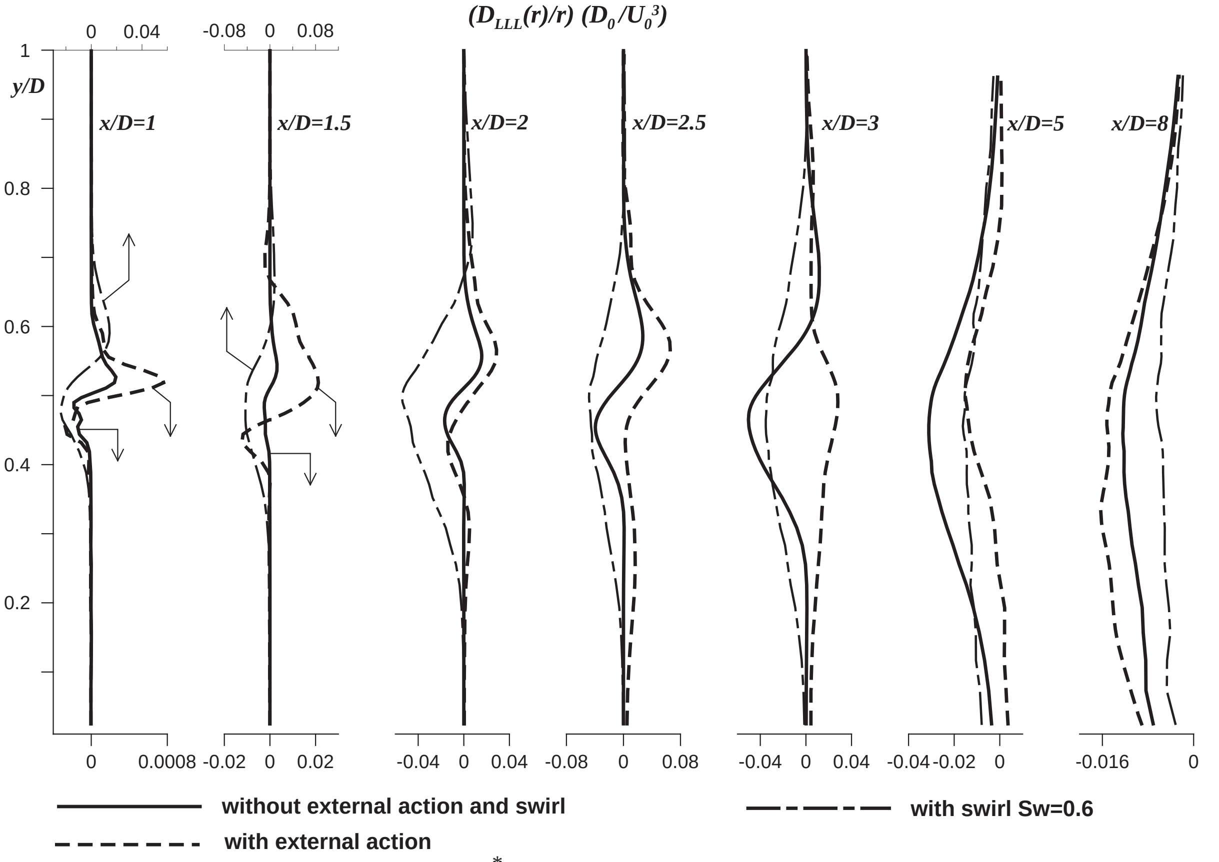

Fig.4. Radial D^*_{LLL} distribution for different *x/D$_{in}$*.

Computations were performed using the supercomputers MVS-6000 and MVS-100k (Joint Supercomputer Center of RAS, Moscow). The work has been supported by the Russian Government Grant (№0035, Ministry of Education and Science of RF, Nov.25, 2010)

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