NUMERICAL SIMULATION FOR PROBLEMS OF AERODYNAMICS ON MULTIPROCESSOR COMPUTING SYSTEMS

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Key words: computational aerodynamics, massively parallel systems, supersonic wing-tip vortices, jet flows, screech jet noise.

Abstract. The renewed interest in the high-speed transport program has created a need for information on wing-tip vortices in supersonic flows. The comparative analysis of experimental and numerical data for M=3 α =10° has shown that computations can predict as a whole qualitative flow pattern in the wing wake. Jet flows have been a subject of intensive theoretical, numerical, and experimental investigations during last several decades. This interest in the first turn concerns the mechanisms of strong noise generated by high-speed jets, in particular very intense tones known as screech. The Euler model has been applied to investigate numerically a supersonic underexpanded jet flow. The numerical simulations have shown the phenomenon of helical instability. The basic result of the present study is that the main mechanism of the screech tone in supersonic underexpanded jets has the nature of blade/vortex interaction in the sound generated by propellers.

1. PROBLEMS OF COMPUTATIONAL AERODYNAMICS FOR AIRCRAFT DESIGN.

The aerodynamic design of modern flying vehicles is a complex scientific - engineering problem[1]. The main goal is the development of vehicle configuration, possessing the required characteristics (drag, lift, controllability etc) in all operational range of Mach numbers and angles of attack and sideslip. The detailed information on of the flow field over a vehicle is necessary for the solution of this problem. The primary tool for the development of aerodynamic configurations was the wind tunnel. The simulation process in a wind tunnel is time consuming and has certain limitations. Computational aerodynamics with the help of high-performance multiprocessor computing systems is an important supplement to the use of wind tunnel. Typical problems of computational aerodynamics include: estimation of the drag, lift, and moment characteristics of the vehicle, development of optimum airfoils and wings for external performance, and inlets, diffusers, and nozzles for internal performance and aero-propulsion integration. Significant progress has been achieved during the last fifteen years due to a wide introduction of multiprocessor computer systems. The massively parallel systems are a powerful tool, which makes it possible to advance the solution of particularly complicated problems of pure science and applied researches. It should be underlined that to use multiprocessor systems effectively it is necessary to take into account and master the specific features of parallel processing in both the construction of computer algorithms and their program implementation. The spatial decomposition of computational domain is a natural method to divide the work among several concurrent processors. One or more blocks are mapped on a single processor. This partitioning should balance the load between processors and minimize the amount of required inter-block communications. The same program runs on each node. Each node program identifies its block numbers with an instance number. Interconnections to other blocks are given by the grid data. Each processor analyses the interconnections and built up the communication requirements. Under correct balancing of the processor loading it is possible to get practically linear speedup of system with increasing a number processors used.

2. INVESTIGATION OF SUPERSONIC WING-TIP VORTICES.

The development of numerical methods for complex spatial flows simulation is impossible without their careful verification. At the present time, various mathematical models are used in computational aerodynamics. First, it is necessary to note models of Euler, Navier-Stokes and Reynolds averaged Navier-Stokes equations. Each of these models has the advantages and lacks. Of course viscous and heat conduction effects are modeled only within Navier-Stokes equations. One of the main difficulties with the Reynolds averaged Navier-Stokes equations is the problem of their closure – turbulence modeling problem. The accuracy of the numerical solution depends on the validity of the turbulence model employed. On the other hand, the Euler equation model allows to obtain many important characteristics of the flow. The question on a degree of adequacy and area of applicability of mathematical model was examined by comparison of numerical and experimental data, obtained in ITAM SB RAS[2,3]. The renewed interest in the high-speed transport program has created a need for information on wing-tip vortices, their characteristics, and subsequent propagation into the downstream wake. Vortices generated by upstream located aerodynamic surfaces of the aircraft can interfere with shock waves generated by aircraft elements located downstream or with the shock wave at the inlet entrance. In many cases, this leads to vortex breakdown, which can worsen the lifting properties of aerodynamic surfaces or be the reason for critical regimes of engine operation. On the other hand the shock-vortex interaction phenomenon is considered as one of the methods for increasing the mixing coefficient in the scramjet combustor.

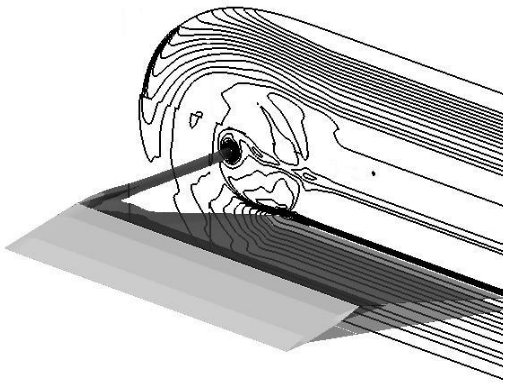

Fig. 1. Flow configuration.

However, experimental and numerical information of this type for supersonic speeds is rather limited[4-6]. To broaden the existing database and to aid in the development of supersonic vortex core model and numerical code validation the complex of experimental and numerical studies was performed. The experiments were conducted in the supersonic wind tunnel T-313 of ITAM SB RAS[7]. A wing-tip vortex is generated by a rectangular half-wing with a span of 300 mm. A hexahedral airfoil has a chord length of 80 mm, a half-angle of 8 deg. The numerical studies included solving three-dimensional steady Euler equations and unsteady Navier-Stokes and Euler equations. Fig.1 shows main elements of the flow configuration.

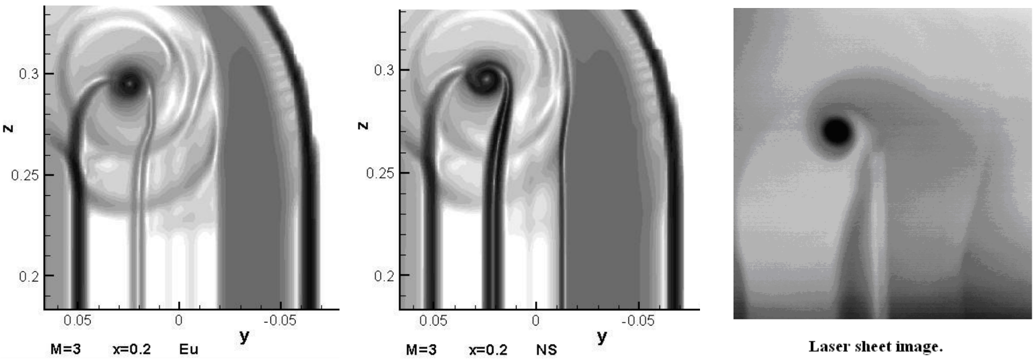

Fig.2. Euler, Navier-Stokes solutions and laser sheet image for M=3 and α=10 deg .

A comparison of visualization and probe measurements results showed that the vortex core, which looks as a dark region in the laser sheet images, is characterized by a decrease in total pressure, Mach number, and axial component of velocity; thus, a wake-type profile is formed. The maximum values of the circumferential velocity as well as swirl ratio correspond to the edge of the vortex-core The Euler solution as a whole predicts qualitative flow pattern in the wing wake reasonably well – Fig.2. But the vortex core corresponds to the region with large Mach number. It is contradicted to the experimental results, where the minimum in Mach number was observed. Computational data of pressure distributions are close to one obtained in the experiments outside of the vortex core. Clearly defined wake-like profile with a minimum of Mach number is obtained in experiments and Navier-Stokes solution - Fig.3.

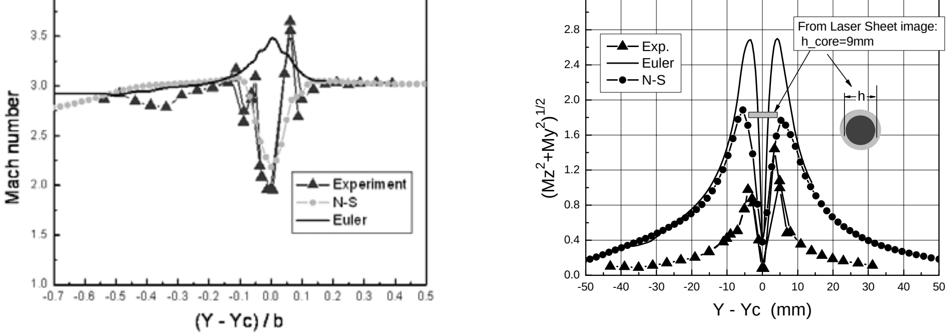

Fig. 3. Total and crossflow Mach numbers distributions through the vortex core.

The crossflow Mach number ($M_{yz} = (My^2+Mz^2)^{1/2}$) is a good estimate of circumferential Mach number. In experiments and both sets of computations classical profiles with its maxima at the vortex core edge are obtained. The tangential velocity is varied nearly linearly from approximately zero to maximum in the vortex core. In the outer region of the vortex core tangential velocity is varying with r^{-1} (where r – distance from the vortex core axis), and asymptotically approached zero. The vortex core edge is defined on maximum of the crossflow (circumferential) Mach number. Fig. 3 indicates that Euler solution can predict vortex core size sufficiently good while the Navier-Stokes solution produce vortex core size some larger than one obtained in the experiments. Fig.3 also shows significant differences in maximum values of crossflow Mach number obtained in the experiments and both sets of computations.

The vortex core center is defined on minimum of both Pitot pressure (Fig. 4) and crossflow Mach number (Fig. 3).

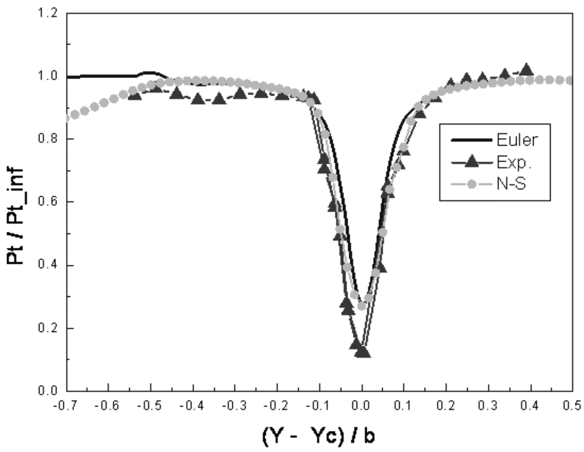

Fig. 4. Pitot pressure distributions through the vortex core.

Euler and laminar Navier-Stokes solutions produced similar Pitot pressure distributions with noticeable loss in the vortex core. Computational data are close to one obtained in the experiments outside of the vortex core. But inside of the vortex core computational Pitot pressure are higher than corresponding experimental data.

So, the comparative analysis has shown that computations can predict as a whole qualitative flow pattern in the wing wake. But the quantitative data on some flow parameters differ noticeably. In Euler computations the “jet-like” vortex was obtained, as against “wake-like” type which was observed in the Navier-Stokes solutions and the experiments.

3. NUMERICAL SIMULATION OF SPIRAL INSTABILITY IN JETS.

Jet flows have been a subject of intensive theoretical, numerical, and experimental investigations during last several decades. Many fluid dynamicists and specialists in computer simulations have endeavored to learn more about very complicated structures in jet flows. This interest have been in the first turn feeding by the desire to understand basic mechanisms of strong noise generated by high-speed jets, in particular very intense tones known as screech (e. g., see a reviews[8]).

As concerning the screech tone, perhaps Norum[9] in his experiments first showed that with increasing intensity of a jet flow a common axisymmetrical instability can drastically change into quite different, flapping and helical, modes that are accompanied by appearance of a high-level sound - the screech sound.

Screech jet noise has been intensively studied with the aim to learn how this sound comes out, what is responsible for its generation, and by which means this negative phenomenon can be eliminated or suppressed. However, in spite of numerous literature devoted to jet flow and screech tones, in particular, there is no still well-established and generally acceptable theory of screech generation. Aeroacoustics phenomenon of a jet is very complicated and involves many interplaying processes (sound due to vortex/shock interactions, turbulence broadband noise, instability, etc.), which makes it difficult to split and clarify a particular phenomenon. For example, in the paper[10], there are computed various instability modes of an underexpanded jet, including axisymmetric and helical modes. The computed results, frequencies and screech modes are well agreed with experimental data. However, any clear explanation of the screech mechanism is not given.

In the paper[11], in contrast, a mechanism of screech is proposed and discussed, which is based on the interaction between roll-up vortices (raised as the result of the shear layer instability at the jet boundary) and the shock cell structure. This mechanism seems to us not adequate to the phenomenon because a strong correlation exists between the screech and the appearance of the helical mode.

In the present paper we try relate the screech with the helical unstable mode and explain how this mode can generate the screech sound. To clarify this relation we choose Euler model for the flow description, which neglects dissipative processes. We strongly believe that the helical mode instability has convective nature and inherent the flow itself; heat conduction and viscosity have only minor effects on it.

We consider the problem of a jet that flows out from a circle nozzle exit into an ambient gas. The ambient gas is in rest and has a pressure that is denoted by P_a and a density denoted by ρ_a. The diameter of the nozzle exit is D=7.8 mm. The nozzle has also a small lip of the length L=1.5 mm.

The jet flow is installed in numerical calculations by setting up a profile of the longitudinal component of the velocity vector u(r), where r is the radial distance, a constant pressure P_e, and a constant density ρ_e in the exit crossection. The azimuthal and radial components of the velocity vector are assumed to be zero.

The velocity profile is taken similar to that used in calculations of [5]:

$$u(r) = 0.5u_e \left\{ 1 + tanh \left[\frac{25}{4} \left(\frac{R}{r} - \frac{r}{R} \right) \right] \right\} \qquad (1)$$

where R=0.5D is the nozzle exit radius, u_e is the maximal velocity (the velocity at the axis of symmetry). Note that no artificial disturbances are superimposed on the inflow velocity field.

The jet flow is characterized by the nozzle pressure ratio parameter $NPR=P_0/P_a$, where P_0 is the stagnation pressure, and the ratio of the exit pressure to the ambient pressure, P_e/P_a.

These parameters are taken to match experimental conditions of [6]: NPR=5 and P_e/P_a =1.73. Under these conditions the exit Mach number (at the axis of symmetry) M_e=1.33 and M_j=1.7, which equals the isentropically fully expanded jet Mach number.

The system of Euler equations is discretized in space with the Godunov finite-volume method. The time integration is performed with the explicit-implicit LU-SGS matrix-free time marching scheme proposed in[14]. This allows us to carry out the calculations with a reasonable time step, which is not restricted by the CFL-condition.

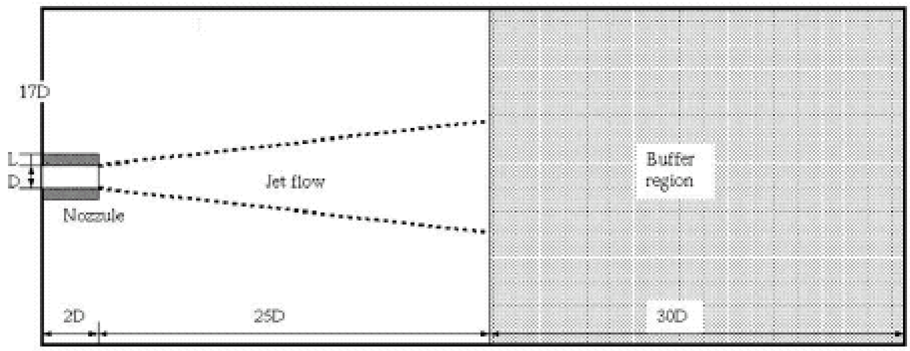

Fig.5. Sketch of the computational domain.

The computational domain is given in Fig. 3. It is represented by two subdomains. One of them is the domain of basic calculations, which expands 17D in the radial direction, and 25D in the streamwise direction. The second subdomain (so-called buffer region) adjoins the basic one along the right-hand side boundary and serves to dump the flow and eliminate undesirable reflections from the outflow boundary. The buffer region expands 30D.

The left-hand side boundary and side (top and bottom in Fig. 5 boundaries are treated as rigid walls. We choose such boundary conditions intentionally because such consideration is absolutely correct from mathematical point of view, although it introduces some misrepresentation of the free jet flow pattern. We believe that the wall effect is not too essential for global structures like the helical instability mode we are interested in.

The grid of the base domain consists of 480 cells in the streamwise direction, 208 cells in the radial direction, and 112 cells in the angular direction. The grid size (in radius) is 0.014D in the jet core; an axial grid size of 0.04D is used to accurately resolve the shock wave structure in the region $0<x/D<12$. The buffer region is covered by a rather coarse grid of 25 cells in the axial direction, which is generated so that a smooth transition between the base and buffer grids is ensured.

All calculations are carried out with parallel processing on the platform of the MVS-15000BM cluster at Joint Super Computer Center of the Russian Academy of Sciences (JSCC RAS). The cluster consists of 1052 CPU IBM Power PC 4 of an overall peak performance of 10 TFlops. Communications are realized on the base of the Myrinet communication media (2.2 Gb/sec) with a full graph node topology; the OS is Linux SuSe, the software includes MPICH, C++ and Fortran compilers.The calculations to be presented have been fulfilled on 100 processors with a time step Δt of 0.5 mcs that corresponds a CFL number of 50. Such choice of Δt allowed us to implement the LU-SGS time integration with only 1 subiteration. Initial data in the computational domain is represented by the ambient gas. Therefore, each calculation starts from start-up conditions, i.e., from the moment when the nozzle flow plunges into the ambient gas. In total the calculation is done for about 100000 time steps, which corresponds a physical time interval of 50 ms.

The noise of high-speed propulsive jets has a broadband spectrum caused in the first turn due to turbulent jet mixing. However, if the jet is imperfectly-expanded, the noise also includes additional components: a highly intensive tonal component referred to as jet screech and broadband shock-associated noise. The former is commonly intensive as much as 40 percent with respect to the broadband noise.

The jet screech phenomenon has been intensively investigated by both numerically and experimentally, and by present there is a received opinion on what plays a major role in producing this kind of strong sound. It is believed that the screech noise occurs due to the interaction between jet large-scale turbulent structures and the shock-cell structure that exists inside the jet.

In particular, the present physical understanding of this noise is discussed in the review of Tam[8]. In accordance with this theory the screech noise requires a feedback loop. It starts with small disturbances, which are originated at the nozzle lip. These disturbances convect and amplify in the developing shear layer. Reaching the second (or the third) shock cell, they interact with the tip of the normal shock. As the large-scale shear layer vortices travel the interaction spot, the tip of the shock wave oscillates significantly, a part of this wave being leaked across the shear layer towards the ambient gas. As a consequence of this, a sharp compression pulse is initiated in the ambient region. Propagating in all directions, this pulse forms a cylindrical compression wave that also travels upstream to the nozzle and closes the loop.

The feedback loop theory predicts a formula for the frequency of screech tones that is in a good agreement with experimental observations. On the other hand, predictions of the amplitude and the screech directivity pattern are not available. Also, it is not well clear from the foregoing consideration the mechanism of the pulse forming from the shock leakage.

The present numerical simulations have led us to propose quite different explanation of the screech phenomenon. Specifically, we state that *the cause of the jet screech is the helical instability and its nature is the drill noise,* i. e., the sound produced by a rapidly rotating drill in air.

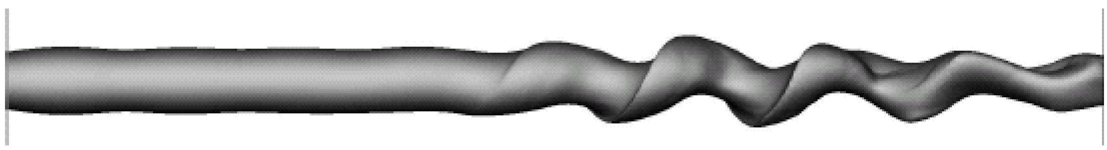

Fig. 6. Isosurface of a density value of ρ=1.7 kg/m**3.

Let us look at Fig. 6, where we show an isosurface of gas density for a value of $\rho=1.7$ kg/m^3 in the case of pure gas jet and dusty jet. This value corresponds a marginal one between the ambient density ρ =1.17 kg/m^3 and the inflow jet density ρ =3.225 kg/m^3, and therefore this isosurface can be considered in somewhat as an instantaneous jet boundary. One can see that the axisymmetrical structure of the jet is destroyed after the forth shock cell (shock cells are not shown in the figure; their length is about 2D) and the jet acquires a typical helical shape, like a drill.

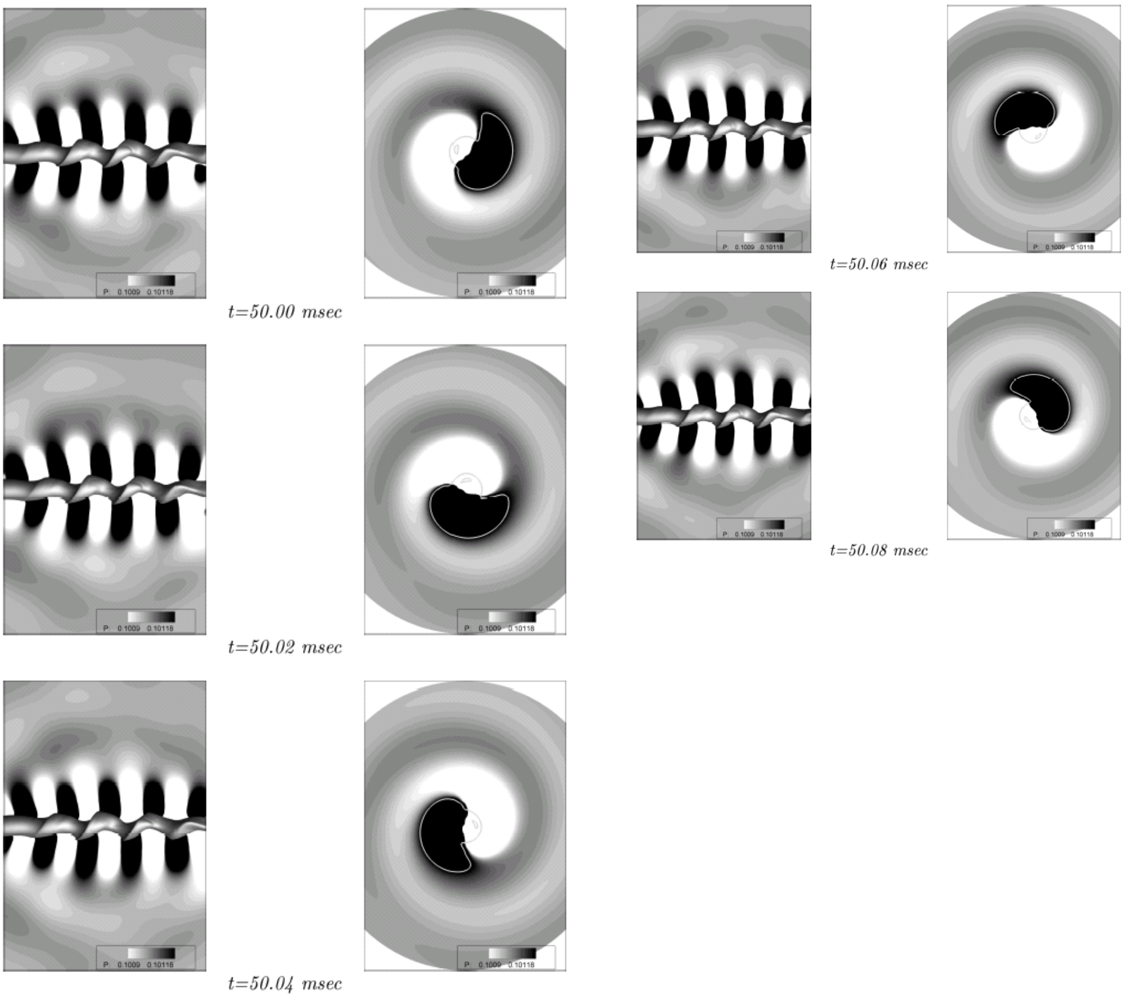

Fig. 7. Jet boundary (ρ=1.7 kg/m**3) and pressure in the ambient gas: meridional plane (left), cross-sectional plane x=13D (right).

This drill-wise shape is not frozen in time. Looking at Fig. 7 where we show the foregoing density isosurface (with the pressure in the near field) for several time moments (left column), one can see that the ripples of this surface seem to run downstream. This visual effect takes place because the surface we are watching rotates as solid in clockwise direction. The frequency of rotations, which easy to determine from Fig. 7, consists 10.58 KHz. Note that this value is rather close to the frequency of screech sound experimentally determined as about 12.8 KHz. Thus, we infer that the jet boundary due to helical instability loses the axial symmetry and takes a form of rapidly rotating drill. The jet gas inside this drill acquires angular momentum; its motion changes from straightforward to spiral (see also Fig. 8).

What happens in the ambient gas when the above helical instability is settled? The effect of the jet flow on the ambient gas is analogous to that of a solid drill (with the same shape as the jet boundary), which rotates with 10580 RPM. Roughly speaking, if imaginary replace the jet flow with the rotating solid drill, the ambient gas would not feel much difference from such substitution.

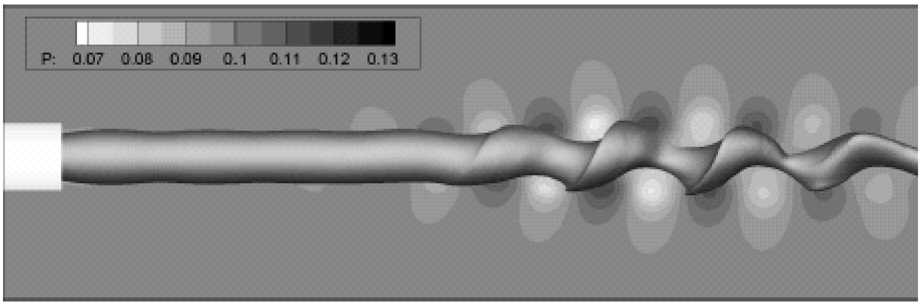

Fig. 8. Jet boundary (ρ=1.7 kg/m^3) and pressure in the ambient gas: meridional plane (left), cross-sectional plane x=13D (right).

A quickly rotating drill generates a tone sound with a frequency that equals the frequency of rotation. The drill has an asymmetry so that when it rotates its cross-section performs up-and-down movement in the meridian plane. Therefore the ambient gas near the drill surface undergoes periodical compressions and expansions, which cause the foregoing sound.

The same mechanism has the jet-screech tone. In Fig. 8 we show the instantaneous jet surface (an isodensity surface of ρ =1.7 kg/m^3) with the pressure contours in the near field for both the gaseous jet and the dusty jet. Zones of generated compressions (dark) and expansions (light) outside the jet boundary are clear seen.

In the Fig. 7 we also show the jet boundary and the pressure field in the cross-sectional plane for several time moments. These figures clear demonstrate how the sound due to helical instability is generated. When the instability appears, the jet in the cross-section takes the form of a blade that rotates around the center. In other words the behavior of the jet in the cross-sectional plane mimics a propeller with one blade in air. Thus, the mechanism of the jet-screech seems to have not the nature of vortex/shock interaction (although this of coarse contributes the overall sound); the main mechanism of screech seems to us to have the nature of BVI (blade/vortex interaction), similar to that observed in the sound generation by a rotating propeller.

Time series data of the acoustic pressure signal $P-P_a$ are picked out and analyzed with the FFT to obtain spectral characteristics of the sound at 3 stations, (r=6D, θ=100 deg), (r=6D, θ =40 deg), and (r=6D, θ =20 deg), respectively. The spectral data (SPLdb vs frequency in KHz) are shown in Fig. 9. The screech tone of 10.58 KHz is discernable in these plots.

Finally, in Fig. 10 we present comparison between experimental and numerical spectral data taken at the second observation station (r=6D, θ =40 deg). The corresponding experiment was carried out at the Fluid Dynamics Lab (Department of Aerospace Engineering, Nagoya University.

Qualitatively the numerical and experimental data are in good agreement. We can see the first, second, and even third modes of the screech in both numerical and experimental curves. Before the first screech frequency the SPL is slightly increasing with frequency, while it rapidly decreases as the frequency becomes over screech. Quantitatively there is no so good matching. First, the screech tones in calculations are about 20 % less then experimental those. And second, the SPL outside the screech tone is overall underpredicted in calculation with respect to experimental data. This discrepancy we explain by a too simplified model (the Euler model) used in our study, which does not take into account many factors of sound generation. However, from another point of view, what we have used this simple model made it possible to refine the screech phenomenon from many other factors and investigate it concretely.

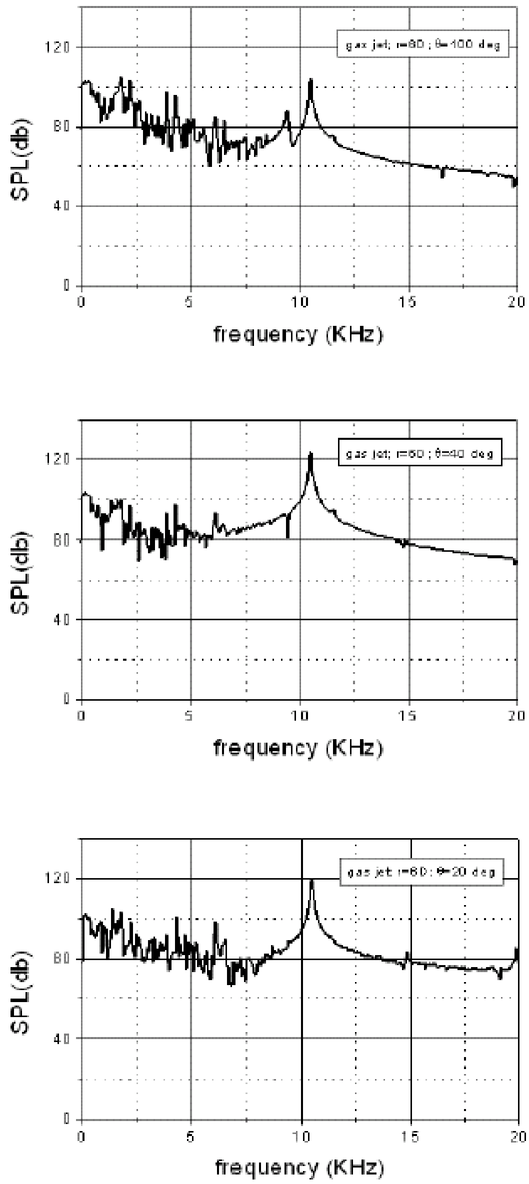

Fig. 9. Spectral characteristics of sound at 3 observation stations.

So, the Euler model has been applied to investigate numerically a supersonic underexpanded jet flow. The numerical simulations have shown the phenomenon of helical instability in its rectified (with no dissipative effects) form and led us to a new physical understanding of the jet-screech. The basic result of the present study is that the main mechanism of the screech tone in supersonic underexpanded jets is not a feedback loop of vortex/shock interactions, which represents the present understanding, but quite different; it has the nature of BVI in the sound generated by propellers. In fact, the jet-screech is of the same nature as the sound generated by a rapidly rotating drill.

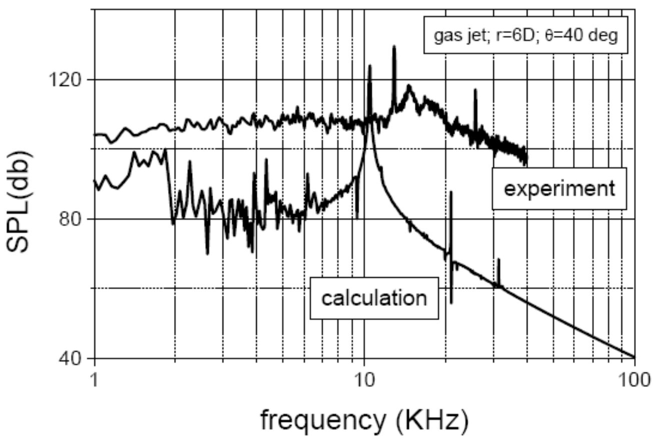

Fig. 10. Comparison spectral characteristics of sound obtained by computation and experiment.

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