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EXPERIMENTAL AND COMPUTATIONAL APPROACH FOR JET NOISE MITIGATION BY MIXING CONTROL DEVICES

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ABSTRACT

The notched nozzle as a new concept has been investigated for conventional nozzle design together with the Chevron nozzle and Micro-jets, through feasibility studies. The notched nozzle has a plurality of triangular pyramid-shaped dent positioned in a circumferential direction along the nozzle exit. These studies include acoustic experiments that utilize a lab-scale simple model in an anechoic chamber and numerical approaches. The results of the Large Eddy Simulation are compared with the results of either acoustic or aerodynamic experiments. The objective of these investigations is to verify the effects of noise mitigation and to gain understanding of the physics of fluid dynamics around the nozzle exit, especially within the shear layer between high velocity jet flow and external flow/or ambient air. One concept of conventional noise mitigation devices involves mixing enhancements in the shear layer, but this sometimes produces high frequency self noise. Moreover it will result in a penalty in terms of thrust loss, additional weight and extra manufacturing cost due to the complicated shapes around the nozzle exit. It is difficult to produce a nozzle design without affecting high frequency self-noise and decreasing low-frequency noise towards to down stream of the jet engines even though there is no thrust loss. Most of this study, the experimental data were physically validated by three kinds of nozzle concepts designed to be equal to the conventional model in terms of size of nozzle exit diameter and Mach number. Essentially far-fields noise measurements and pressure measurements are conducted by polar angle microphones and arch-shaped pitot tubes are located downstream of the jet. The noise benefit which is produced by the notched nozzle as a lab-scale in far-fields noise measurements is up to 1.3dB at the side of the jet and 0.5dB at downstream, in terms of size of small-engine.

Furthermore this provided an advantage over the chevron nozzle due to the decreasing self-noise production when the Mach number of the jet was lower than 0.9. Moreover, numerical predictions which are provided by the Large Eddy Simulation were used to estimate the noise mitigation by performing turbulence statistical analysis. Numerical results which refer to the turbulent statistics are discussed in order to define how they can be affected to the acoustic results at the side of the jet. This shows how each device can deform the shear layer without producing additional streamwise and small scale vortices.

NOMENCLATURE

TKE: Turbulence Kinetic Energy
LES: Large Eddy Simulation
EXP: experiment results in anechoic chamber
ICAO: International Civil Aviation Organization
EPNdB: Effective Perceived Noise Level in Decibels
PNLdB: Perceived Nose Level in Decibels
SPL: Sound Pressure Level
OASPL: Overall Sound Pressure Level
Q-criterion: a second invariable of shear strain tensor

1. INTRODUCTION

The conventional criteria of noise for civil aircraft is gradually being strengthen from ICAO (International Civil Aviation Organization) Annex 16 Volume1(Chapter2) which was established in 1971, to Chapter 4 in stages[1], [2].

Chapter 4 introduced a regulation of cumulative noise margin, regarding three measurement points: fly-over, approach and lateral points for subsonic jet aircraft which has been made application since January 1st 2006. In addition, what is important in lateral and fly-over measurement points is to take flight effect into account. To put it briefly, it is given by the maximum value of noise on lateral line which has several measurement points. The Fig.1 tells us the flight effect.

The regulation needs to be satisfied for Chapter 3, not only each at measurement point but also the sum of noise should be less than 10EPNdB (Effective Perceived Noise Level in Decibels) furthermore, the margin for sum of 2 points should be at least more than 2EPNdB in Chapter 4. On the other hand, study for noise stringency options are also starting to create new regulation. It has been recognized by each air-port that many types of local rules reflects an environmental condition and an area, however it is difficult for people to understand how important the values of the 1EPNdB for aircraft noise are. Needless to say, it is quite hard for human to recognize their difference of 1EPNdB by using their own ears. But from the view point of noise mitigation, 1EPNdB deserves careful attention in the certification of engine noise, regarding the regulation for three measurement points which has been introduced above**.**

Generally, the Jet-noise is still a dominant source of engine noise during take-off even for a civil modern high bypass engine. Over the past few decades, a considerable number of studies have been conducted on the geometry of mixing devices for jet-noise mitigation [3], [4], [5], [6], [7], [8]. To put it briefly the reduction of noise can be a result of the decreasing of jet-velocity by implementing a high bypass ratio. Many types of mixing devices on the exhaust nozzle have been studied for a low bypass ratio engine, a small thrust engine and conventional high bypass engines, in attempt to enhance a mixing between two types of shear layer such as core flow and fan flow or bypass flow and ambient. As a result of these, the jet-velocity of the engine would be reduced to gain the noise mitigation, however, it has been recognized that a thrust penalty always results due to loss of large scale mixing devices [6].

According to recent studies, a mixing device that can enhance the mixing of shear layer is made of triangular serrations, looks like shark teeth, and it is called "Chevron Nozzle". It has already been implemented in both military and civil engines. Numerous studies have focused on this type of mixing device. Martens utilized the F404-400 (for early F-18) to investigate its effect on noise mitigation and thrust penalty [7].

Callender and Bridge conducted parametric studies for geometry of chevron by acoustic measurements and also PIV measurement [8], [9], [10]. Concerning civil aircraft engines, Nesbitt et al. has investigated a full-scale flight test under the project of next generation civil aviation, named Quiet Technology Demonstrator (QTD) [10]. This test describes the performance of chevron nozzles which were installed only in terms of the bypass or core or respectively both. According to this study, the chevron row which is azimuthally varying along nozzle exit is able to decrease the thrust penalty owing to lean angle. It was possible to reduce jet-noise in SPL of almost 2dB and also been accomplished in the thrust coefficient at cruise less than 0.05% or take-off condition.

In the connection above, Saiyed et al. carried out parametric studies of chevron for middle-scale model of double flow rig via chevron or a tab [11]. Schlieren Photos, investigation of noise source, measurement of thrust has been conducted at three Mach number of flight conditions, 0.8(cruise), 0.28(take-off) and 0.0(ground). After due consideration of results, chevron and tab did not have a significant benefit in terms of jet noise mitigation in subsonic jet condition. Nonetheless, the best configuration in their test found that it is necessary to equip the chevron to both core and bypass duct respectively which resulted in a successful gain of 2.7EPNdB with only 0.06-point cruise loss.

Mixing of shear layer by micro-jet was also recently investigated in detail [12], [13], [14], [15], [16], [17]. It is a possible that this active device could produce controlled noise benefits with respect to flight conditions. It is also important to discuss micro-jet phenomena in terms of noise mitigation however; this topic will not be covered in detail in this paper.

A number of relevant studies have helped to create new points of view on numerical approaches [18], [19], [20], [21], [22], [23]. A Large Eddy Simulation has been carried out by many researchers thanks to significantly improvement performance of calculators. It can give a better understanding of the flow field of the jet even though geometry, such as the chevron nozzle, is very complex.

Bogey compared quantitative discussion with experimental data for jet noise directivity. He gave an inlet-disturbance within the jet in order to demonstrate practical disturbance of the jet by large eddy simulation [18]. Spallart carried out LES applied to double flow configuration in comparison with experimental data [19]. On the other hand, Liu studied LES for configuration of the micro-jet nozzle [20], [21]. This has shown the effect of mass flow rate of the micro-jet within the shear layer deformation and noise mitigation. As described in this paper, the micro-jet was able to deform shock structures by penetrating of the micro-jet, furthermore, the main jet potential could be extended to the downstream. Huet et al. demonstrated the feasibility of numerical studies both aerodynamically and acoustically on active control of jet flows. They argued that the grobal over-estimation of kinetic energy and of far field noise was observed but effect of the control on the jet is correctly computed [22].

This article is intended as an investigation of understanding of the flow-field of a mixing device which has been studied under the ECO-engine project [12], [23] one of Japanese research and development project for the environmentally compatible engine. Then we would like to discuss what is related with the noise mitigation, in terms of deformation of shear layer by notched nozzle which is designed by IHI. The notched nozzle has a small scale projection from its surface inside of the nozzle, in the shape of a triangular pyramid. The scale of a notch is very small, in order to reduce the costs of mixing devices in terms of manufacturing, repairing. Furthermore it may result in smaller thrust penalty from a design point perspective, keeping an overall noise benefit. By definition, this patent is characterized by its device size compared with conventional mixing devices. This device results in only 2-5% penetration of height to the core flow of each notch moreover the number of notches were determined as 8 to 18 based on the acoustic experiments in hot jet condition; however, there is still room for discussion how quantitative benefit could be produced for conventional devices such as a chevron type device [10],[11].

The early study of notched nozzle as shown in Fig.2 (A) was conducted in the form of noise test trial using a lab-scale model [12]. Other studies have also been conducted. In the next figure, Fig.2 (B) shows a turbo jet engine that was employed as a jet noise demonstrator which is a single-shaft, axial-flow and centrifugal compressor and single stage of turbine, which provides more than 800 kg of thrust while in static condition. Noise measurements and also pressure and temperature measurements were taken during static condition, with notched nozzle and base nozzle. Then, as a result of the above, we tried to prove the concept of notch in a large-scale model noise test in flight condition. This test was conducted by IHI at the large-scale acoustic test facility in England (Qinetiq), shown in Fig.2(C) [12]. It gained almost 1EPNdB as a noise benefit with the notched nozzle (compared with conical nozzle). Moreover, the effect of pylon has also studied during this experiment but the optimization of the pylon remains a matter to be discussed further. Fig.2 (D) shows the small-scale rig which was created to optimize the notch configuration in terms of aircraft engine design. As can be above, we tried to improve notched nozzle but there is a further question which needs to be discussed in detail, why does the notched nozzle have additional benefits when compared to base model. In this article, we discuss several characteristics of the differences between notched nozzle and chevron nozzles in terms of LES and experimental results.

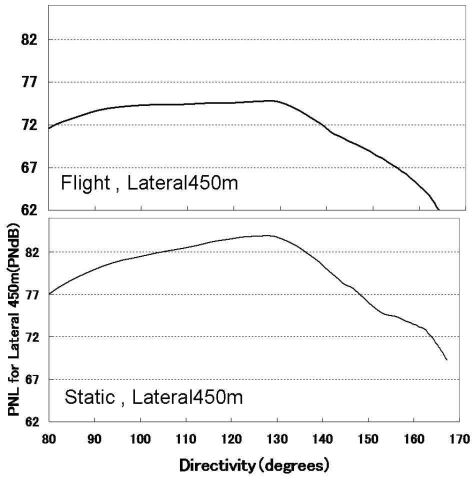

Fig.1 Flight effect for jet noise directivity on lateral 450m [12]

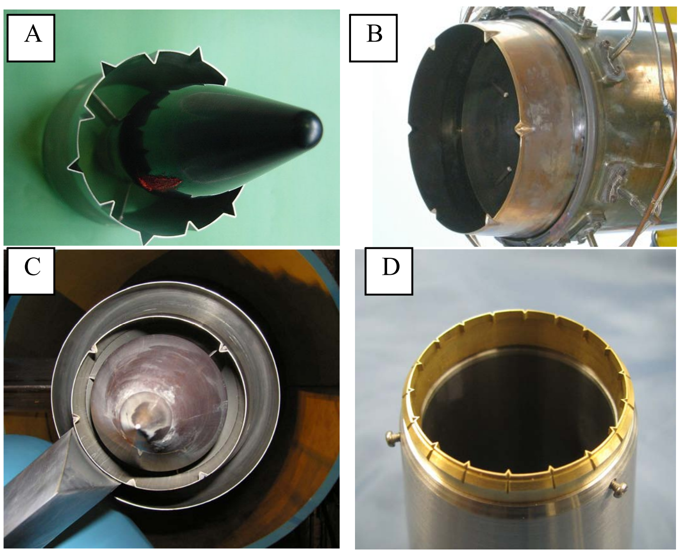

Fig.2 optimization for the early notched nozzle
A: Early notch, B: Actual engine test
C: Large-scale rig test, D: lab-scale rig test

2. NUMERICAL SIMULATION

2.1 Methodology of Large Eddy Simulation

The jet noise analysis should be resolved small scale vortex in order to calculate small pressure fluctuations for acoustic propagation. Therefore, LES has been brought to public attention in the study of jet noise over the past few decades. We also selected a solver which is named UPACS-LES [24], was based on a common program UPACS has been developed by Japan Aeronautics Exploration Agency (JAXA).

UPACS-LES is an unsteady three dimensional filtered compressible Navier-Stokes solver based on finite volume method using multi-block structured grids. The convection term is discretized by high-order compact scheme for finite volume method, and a low storage four-stage Runge-Kutta method is implemented for time integration. Smagorinsky model is used for the subgrid scale stress model of LES, and Cs=0.1. The convection term was discretized by compact scheme for finite volume method with formally 6th-order. In the compact scheme for finite volume method, cell-face quantities are reconstructed from cell-averaged quantities, and the fluxes on the cell-face are calculated from the reconstructed quantities:

$$\alpha\hat{q}_{i-\frac{1}{2}}+\hat{q}_{i+\frac{1}{2}}+\alpha\hat{q}_{i+\frac{3}{2}}=a\frac{\bar{q}_i+\bar{q}_{i+1}}{2}+b\frac{\bar{q}_{i-1}+\bar{q}_{i+2}}{2} \tag{1}$$

Where $\bar{q}$ on the right hand side denotes cell-averaged quantities and $\hat{q}$ on the left side denotes reconstructed value at cell faces. 6th-order is achieved when the coefficients are,

$$\alpha=\frac{1}{3},\ a=\frac{29}{18},\ b=\frac{1}{18} \tag{2}$$

The scheme maintains 6th order only when the computational grid is equally spacing orthogonal grids. On the general curvilinear grid, it maintains 3rd order. At the interface between each block, 4th order explicit scheme, that is

$$\alpha=0,\ a=\frac{533}{420},b=-\frac{139}{420} \tag{3}$$

is used in order to avoid accessing the variables of adjacent blocks. To prevent numerical odd-even oscillation, a compact filter, whose order of accuracy is up to 14, was used

$$\alpha\hat{q}^*_{i-1}+\alpha\hat{q}^*_i+\alpha\hat{q}^*_{i+1}=\sum_{j=0}^{7}a_j\frac{\bar{q}_{i-j}+\bar{q}_{i+j}}{2} \tag{4}$$

$\bar{q}$ on the right hand denotes original value, and $\hat{q}^*$ on the left hand denotes filtered value. The filter is the same as the method of Gaitonde et al, but it does not use one-sided filter near the boundaries, instead, we used lower order central filter near the boundaries in order to avoid phase error.

2.2 Mesh information

In this article, we selected the sector model for LES however it must be examined dependence for mesh strategy why the sector model could resolve actual flow-field of the jet as well as a whole jet. Tab.1 is indicating three types of mesh configuration, coarse mesh, fine mesh, sector mesh. In order to validate of the effect of mesh density or sector, we have carried out the LES and got time-averaged results which was shown in Fig.4 compared with the PIV data which was given by Castelain et al. To put it briefly, there is exactly exited dependence of mesh density for shear layer resolution, however if we could put the suitable number of mesh density, the shear layer would be quite similar to the experimental results. At the view point of cost because of the LES obviously needs to spend lots time and resources, we should take the parametric study for geometry of those devices into account, furthermore, this study has been focused on the shear layer deformation, finally, we decided to use sector model in this study.

Tab.1 Mesh information

	grid points	delta x	micro jet	region
coarse	28M	0.013D	2x2	x<30D
sector	11M	0.005D	4x4	x<3D
fine	476M	0.005D	4x4	x<20D

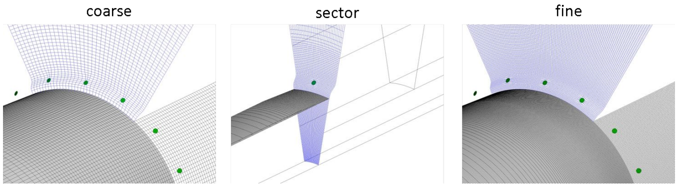

Fig.3 Mesh verification for three types of configurations

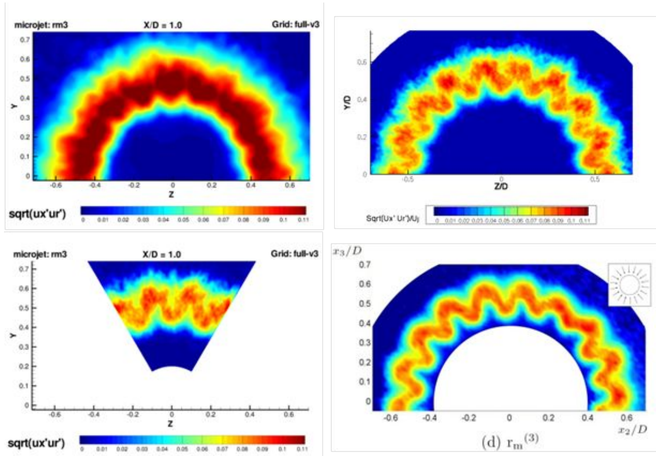

Fig.4 Shear layer deformation at x/D=1.0, micro-jet blowing condition with almost 1%mass for core jet
(A) Coarse mesh, (B) Fine mesh
(C) Sector mesh, (D) Exp by Castelain [13]

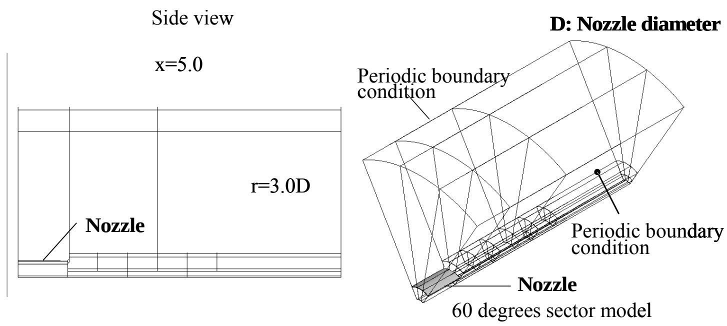

Fig.5 Basic domain configuration for LES

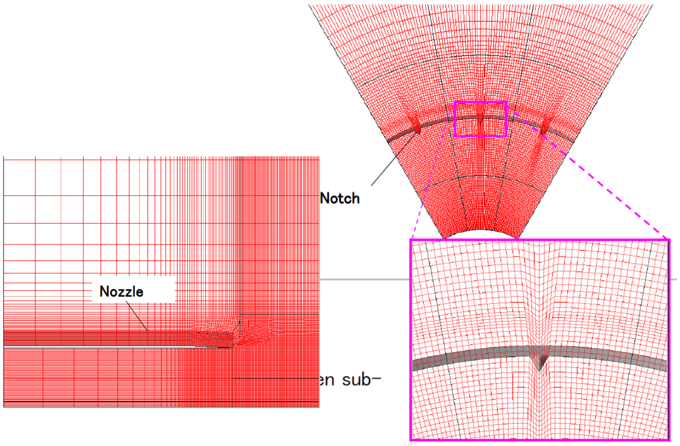

Fig.6 Mesh geometry of the Notched nozzle

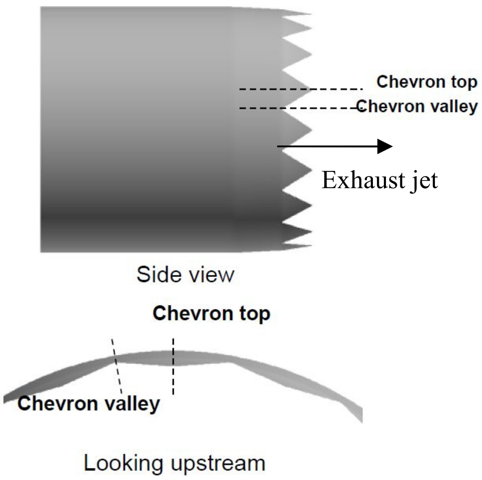

Fig.7 Chevron nozzle

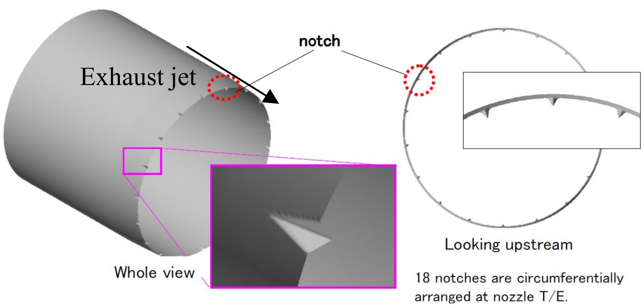

Fig.8 Concept of the Notched nozzle by IHI

Fig 5 shows the domain for LES that whole jet was divided by 6 as a sector model. It reached 5D (D is showing a diameter of the nozzle) from nozzle exit as an analytical region, and also has 3D for radial direction. It can be seen that the center region was excluded from the domain, as like an annular, is to save the time for LES in order to calculate by small number of CFL. The simulation has carried out in JAXA Supercomputing System (JSS), located in Chofu in Japan. The mesh configuration is indicating in figure 6 was made up with almost 11 million points within 39 multi-blocks. Both Chevron and Notched have 18 devices for an each 20deg interval in azimuth direction; therefore, it can be divided as 3 devices in 1/6 sector (120deg) within. As shown in figure 4, the shape of chevron was referred from a type of Alkislar's experimental facilities (16). The number of chevron was determined equal to notch.

On the other side, an inlet boundary condition was yield by nozzle pressure ratio and total temperature ratio into the upstream of the nozzle together with distribution for boundary layer. It was determined a Mach number at nozzle exit as 0.9 by inlet condition. There is no ambient flow and the buffer region was set up from 5D to outlet of domain not to affect unphysical affecting to analytical region by exit boundary condition. Inlet disturbance was given into a boundary layer within the nozzle at x/D=-0.2. Inlet disturbance assumes that turbulence boundary layer is developing within the nozzle owing to be natural growth of turbulence in shear layer after the nozzle exit.

2.3 Estimation of Turbulence Parameters

The most difficult point for analyzing of jet noise is needed to resolve much different size of vorticities in domain. Basically a lot of small vorticities are produced nearby nozzle exit because of strong shear stress and after that, they will be mixed up with ambient, merging, growing up to be more bigger size vorticities. They become large scale vortex toward to downstream; therefore, the acoustic jet directivity should be obtained the effect by all size of vortex. But the sector model is too small to take all effect of vorticities into account. Thus we should limit the discussion to nearby the nozzle exit where is noise source of high frequency noise due to the small scale vorticities (25).

An equation of turbulence kinetic energy is given by equation (5). The velocity perturbation was performed in the shear layer as a vector for each direction could be denoted as follows;

$$\text{Turbulence Kinetic Energy} = \frac{1}{2}\left(u_x'^2 + u_\theta'^2 + u_r'^2\right) \Big/ U_{jet}^2 \tag{5}$$

And then, the Reynolds stress is performed by velocity perturbation using expression of tensor for uniform flow condition is shown in equation (6).

$$\text{Reynolds Stress} = \rho u_i' u_j' \Big/ U_{jet}^2 \tag{6}$$

Radial diffusion of turbulence could be modified by a square root of turbulent diffusion is defined in as a expedient expression,

$$\text{Reynodls Stress} = \sqrt{u_x' u_r'} \Big/ U_{jet} \tag{7}$$

The remarkable point for this methodology, there is no distinction for frequency of sound wave in values of turbulence kinetic energy and also Reynolds stress, therefore, it can not maintain as a sound pressure level: SPL if they had obviously difference of turbulence kinetic energy or Reynolds stress for each mixing device. As the purpose of this article is concerned, it is not necessary to discuss them so far.

2.4 Capturing Vortex Structures on Q-criterion

While the velocity is changing in the domain, the elements of fluid were deformed by other elements; therefore, they could be defined based on local velocity gradient, as follows,

$$u_{i,j}(x,t)=\frac{\partial u_i}{\partial x_j} \tag{8}$$

In addition to velocity gradient tensor u_{ij}, they have two parts of their equation in which are multiplied with symmetry portion and asymmetry one. The former portion could be defined as velocity deformation tensor S_{ij} and then later portion could also be defined as vortex tensor w_{ij}, so-called q-criterion; it was evaluated by subtracting velocity deformation tensor from vortex tensor. The q-criterion was defined by,

$$Q-criterion=\frac{1}{2}\left(u^2{}_{i,j}-u_{i,j}u_{j,i}\right)=-\frac{1}{2}\left(\Omega_{i,j}\Omega_{i,j}-S_{i,j}S_{i,j}\right) \tag{9}$$

$$\Omega_{i,j}=\tfrac{1}{2}\left(u_{i,j}-u_{j,i}\right), S_{i,j}=\tfrac{1}{2}\left(u_{i,j}-u_{j,i}\right)$$

In equation (6), it was inspired only swirl term by a vortex from the effect of vortex tensor which has both swirl and gradient. Equation (6) is often utilized to identify stream wise vortex structures in boundary layer such as a flat plate etc [26]. There is no specific value of q-criterion, thus we selected a value to be observed shear layer deformation clearly in the domain, therefore, Q = 2 was selected.

To discuss the rotation of vortex which was produced by device is needed to define a scalar function by non-dimensional helicity. It could be defined that the difference of colors indicate the rotational directivity of vortex and color in red is indicating as clock-wise and else blue is indicating as anti-clock-wise rotational directivity of vortex when we watched the nozzle from downstream.

3. EXPERIMENTAL APPROACH

3.1 Nozzle Configurations for Acoustic Experiments

The results of LES is limited the discussion to flow-field nearby the nozzle exit as I mentioned above, therefore the noise test is necessary to verify our estimation of device, thus we have conducted the noise test same as LES configuration.

The base nozzle was designed as 40mm diameter lab-scale model besides, two types of nozzle were also made which based on the base nozzle and their orientation of nozzle exit is corresponding to the base nozzle. Figure 2(D) shows the notched nozzle which can be replaced for several types of notch configuration only removing a ring of nozzle exit.

For the lab-scale test with only cold jet, the anechoic chamber is 4100 x 5700 x 3300 mm with polar stand for microphones which were located for each 10deg interval from 20 deg to 110deg. The exhaust nozzle exhausts the vertical jet to ceiling duct, besides the valve for the main jet, PID control with regard to the pressure inside the chamber, can control Mach number from 0.4 up to nozzle pressure ratio 2.4 that it is actually incompletely expansion condition.

Several 1/4 inch field-type microphones with pre-amp, B&K Type 4939 & 2669, 1dB accuracy less than 100 kHz, equipped at least 1500 mm (38D) from the exit of nozzle. Acoustic signal could be gathered by 200 kHz sampling frequency, using a signal conditioner, GRAS type 12AG, is available up to 80 kHz and averaging 10sec for every measurement point.

In addition, the multi-probe Pitot tube which has 15 holes was also equipped to measure total pressure distribution from nozzle exit to 5D downstream for every axial position for 60 sec recording by 5 kHz sampling. It can be given pressure distribution of whole jet by rotating 360 deg. We checked the time-averaged pressure filed whether it correspond to time-averaged results of LES.

3.2 Pressure Measurement

In the experiments, we conducted the pressure measurement by a pressure rake, in order to check the shear layer in the jet, in terms of Conical nozzle, Notched nozzle and Chevron nozzle. In addition, we checked the boundary layer thickness whether it was practical in LES that was putted into the inlet boundary as a pressure distribution and disturbance that I mentioned in 2.2. Fig.9 summarizes the results of the pressure map in comparison with the LES result at same orientation for x/D, x/D=0.5 and 2.0. The left six pictures in Fig.6, is showing the pressure distribution both EXP and CFD at x/D=0.5. The right 6 is also showing both at x/D = 2.0. The result of sector is copied for azimuth in order to compare with experimental results. The Conical nozzle naturally distributed uniformly and the thickness of boundary layer is quite similar to the CFD results. On the other hand, the notched nozzle and chevron nozzle are clearly seen the deformation of their shear layer which was caused by own device in upstream. The all CFD result of deformation was underestimated than experimental result. This seems to have several reasons due to accuracy of measurement or effect of excluding the centerline of the jet in the LES domain or other of them. But it is not such a big deal to compare each deformation of shear layer of mixing device.

We realized that they have same features of deformation of shear layer between notched and chevron nozzle in the left side of Fig.6, however, the notched nozzle is obviously different from chevron nozzle in terms of the patterns of deformation. In the case of notched nozzle, both EXP and LES are smoothly deformed by 18 notches, on the other hand, the shear layer of chevrons are deformed with narrow edge of shear layer which is indicating a strong mixing between ambient air and jet flow. At x/D=2.0, at last, there is no difference between both devices. As a consequence, the difference can be found at nearly exit of nozzle, x/D=0.0 to 2.0, especially, the patterns of deformation.

4. Results and Discussions

4.1 Mach Contours nearby Nozzle Exit on LES

Fig. 10 shows the Mach number contours by time-averaged LES result nearby the nozzle exit of conical nozzle from x/D=0.0 to 2.0. The 1/6 sector is expressed by three areas isolated by black line. The growth of shear layer toward to jet downstream of conical nozzle was quite azimuthally uniform in terms of each view of cross-section.

Figure 11 is also showing the Mach number contours that it can be formed as a deformation of shear layer by notches. In this case, a small scale notch (it is just 3% height for diameter) was able to deform shear layer to centerline. However, the deformation could not see after x/D=1.6 because of the dissipation of the jet.

Figure 12 is showing the Chevron case, and it is slightly different from notched nozzle. The shear layer was sharply deformed by the chevron penetration and the flow element leaked from between each chevron. Because the chevron has few angles which can lean the flow element to the centerline. As a result, lean angle is equal to the penetration, namely a narrow shape of shear layer will help shear layer mixing between ambient and inside of the jet.

4.2 Explanation for Flow Structures by LES

At the next stage, in Fig.13 to 15, the representative iso-surface, Mach number = 0.4, the vortex structures and turbulence kinetic energy distribution were indicated in the figure for each condition, conical, notch and chevron.

A conical nozzle in figure 13, two pictures were indicated by mach iso-surface (upper) which was colored by turbulence kinetic energy and also vortex structures defined by Q-criterion. The Q- value was defined by the rotational directivity using non-dimensional helicity. Firstly, we noticed that the turbulence kinetic energy was rapidly produced in the shear layer after a small gap from nozzle exit. Moreover, numerous vorticities exit along the nozzle lip and they seem that quite homogeneous but random vorticities are.

The Notched nozzle was shown in figure 14; the notch can actually deform the shear layer by its penetration. The deformation spread through from the edge of notch to downstream. And after that, the deformation would azimuthally encounter each other and merged. The deepest penetrating was occurred in downstream of notch, marked by “A”, which produced high turbulence kinetic energy. The notched nozzle was successfully able to deform the shear layer by small notch, especially, there are no such a big vortex structures. Only small scale streamwise vorticities were produced nearby a notch. It is quite similar to the conical case.

The Chevron case is showing in Figure 15, the shear layer forms alternated deformation which is quite different from notch case in terms of the patterns of deformation. The fluid element was leaked from between chevrons, thus, “B” in the bump of iso-surface is indicating the strong deformation of shear layer. Furthermore, the highest turbulence kinetic energy was produced in the valley between bumps where the region “C” is showing in Fig.15. As the Fig.15 indicates, the bump was consisted with the typically streamwise vortex. The feature of those streamwise vorticities is a strength and direction. The color of non-dimensional helicity is indicating the opposite rotation of each vortex. As a result, this a couple of vortex enhanced the circumferential mixing between the bump that is why the region “C” was resulted the highest turbulence kinetic energy could be produced here.

To say the matter simply, both Chevron and Notched nozzle can result the shear layer deformation similarly, however, the significant difference exist until x/D=2.0. We can represent the bird’s view in a figure 16 in comparison with both cases. The sector models were azimuthally arranged in order to understand the shear layer deformation. As I mentioned above, a composite visualization for Mach number, turbulence kinetic energy and Q-criterion with non-dimensional helicity was illustrated in Fig.16 by the same way for Fig.13 to 15. However, as for the turbulence kinetic energy, the notched nozzle was able to decrease it than Chevron, in particular the iso-surface Mach =0.4. More accurately figure is showing in figure 17. Here is showing the 1/6 sector view which was inspired from Fig.13, nearby the nozzle exit. The recirculation region was formed along the nozzle exit in the case of Chevron, however, the notched nozzle does not have so strong recirculation nearby the exit. The Mixing region is indicating in Fig.17 that was colored by high turbulence kinetic energy. In the case of Chevron nozzle, a bump rise from the nozzle exit due to the leaning of Chevron, then, the valley between the bump was leaned by Chevron but the flow element would expand from the nozzle exit. For this reason, a couple of vortex is formed due to the shear stress. On the other hand, the notched nozzle did not lean the jet directly but also just small scale penetration was existed in the downstream of notch. The mixing region is not located in same orientation compare d with Chevron nozzle. The jet was naturally expanded as like the case of Conical nozzle. Therefore, there is no strong vortex and recirculation region.

We have been demonstrated the turbulence kinetic energy or Reynold’s stress in the same value of iso-surface, however, all Mach number should be taken into account when we discuss the growth of turbulence kinetic energy toward to downstream for an each nozzle condition. Therefore, Fig.18 are showing that the maximum value of turbulence kinetic energy or Reynolds stress in the same x/D surface in addition, the case of conical nozzle were also illustrated on background of graphs. Generally, the turbulence kinetic energy and Reynolds stress are growing up to downstream, however, what is important is the growth ratio of those parameters. In Figure 18, the notched nozzle was observed that the turbulence kinetic energy and Reynolds stress were significantly lower than the Chevron until x/D=2.0. After that, both Chevron and Notch model were gradually decreasing the level of turbulence kinetic energy than the Conical.

In fact, the turbulence kinetic energy and Reynolds stress were reduced in the case of Notched nozzle, thus, the noise source should be reduced based on our assumption. This has been discussed above, however, in terms of acoustic results; the fundamental questions were still remained unanswered. Because the turbulence kinetic energy and Reynolds stress can not transfer to the sound pressure level in this article. Especially the discussion of LES in this article should be limited nearby the nozzle exit; however, in terms of design of noise mitigation device, it could promptly be compare with other case even though using the LES. Therefore we conducted the experiment for acoustic test in the next chapter, in order to prove this assumption that we have been stated above.

Whether this assumption can be proved or not is open to discussion, but we are going to discuss the assumption after the next topic.

4.3 Acoustic Results on Experiment

In the results of time-averaged LES, we recognized that the notched nozzle could deform the shear layer as same as chevron nozzle but without strong vortex structures in the flow-field. We think, the turbulence kinetic energy and Reynolds stress are related to the noise generation nearby the nozzle exit, then they would offers the key to an understanding of designing of noise mitigation device.

In this section, we conducted the verification of the design of notched nozzle which was selected by the results of large eddy simulation, is a lab-scale nozzle (D=40mm, height of a notch is almost 1mm) in acoustic chamber.

Figure 19 is indicating the 1/3 octave band spectrums at 20deg for the angle from jet exhaust axis (downstream of the jet), 60deg (oblique forward of the jet), 90deg (sideline of the jet). The sound pressure level was observed by a microphone array for all configurations of nozzle, Conical nozzle, Notched nozzle and Chevron nozzle. The overall sound pressure level: OASPL is also aligned in the left of figure 19. In terms of 90deg, the noise benefit was appeared during a low frequency band less than 20 kHz. In the high frequency band, the Chevron nozzle caused an additional noise than the Notched nozzle and the Conical nozzle. The notched nozzle was successfully able to suppress own high frequency noise, keeping the noise benefit in low frequency. Moreover, at 60 deg, the almost 2dB benefit for the SPL was also observed by both; on the other hand, the additional noise could not remove from in the high frequency band. Next, at 20deg, the Chevron nozzle archived significantly noise mitigation than the Notched nozzle, however, the noise benefit was decreased by a additional noise in high frequency band, therefore, the notched nozzle scored OASPL which is close to the Chevron's one.

The experimental results proved what we have been discussed before, an additional noise was obviously obtained when the device enhanced the mixing, more concretely, the strong streamwise vorticities must be existed by deformation of fluid element in the shear layer. In other word, the notched nozzle was able to deform the fluid element without significantly additional noise in fact.

Further discussion has carried out by using a tool that is the correction for noise of lab-scale to the noise of actual engine size, obtaining atmosphere damping factor. We assume one outer diameter of core nozzle for the engine size as 400mm is almost similar to eco-engine and added the perceived correction to that tool in order to compare the influence of additional noise. In addition to this correction, the distance from the noise source was determined by following a reference point which was suggested by ICAO, was 540m (lateral 450m on the ground with 300m for aircraft altitude) beside of the engine (90deg) and microphone would be equipped along a lateral line for an each angle. In figure 17, a result of noise benefit on PNL was indicating as bars for each station. A horizontal line is indicating an angle of each station from a reference point. High number of angle means a downstream of engine along the lateral line. According to the results of SPL that I mentioned above, the significantly high frequency noise was observed in the case of Chevron nozzle. The Notched nozzle was also observed additional noise in high frequency band, however; it was lower than Chevron nozzle. The pattern of SPL shifted to low frequency band because the geometry effect was taken into account.

At the point of 90 deg, it was found from the result that the benefit of Notched nozzle is approximately 1.2 PNLdB larger than Chevron nozzle. However, in aft-angle, the Chevron nozzle got the benefit than the Notched nozzle. What has to be noticed here that we have been discussed only nearby the nozzle exit that can be explained, we could not optimize the configuration of Notched nozzle for downstream noise mitigation. In consequence, the additional noise is deeply connected with the practical noise benefit in order to optimize the noise benefit, namely the scale effect should be taken into account.

5. Conclusions and Future Discussions

We carried out the large eddy simulation by a 1/6 sector model in order to understand what was occurring nearby the nozzle exit for each configuration of device. The result of LES was utilized to estimate the turbulence statistics such as a turbulence kinetic energy and Reynolds stress, and then, the significantly differences was observed in the flow-field. The Notched nozzle which was designed by IHI, was successfully able to suppress the turbulence kinetic energy and Reynolds stress than Chevron in LES.

In order to prove the noise performance of Notched nozzle for lab-scale noise test was conducted. As a result of test, the noise benefit was gained in limited angle. After all, the important investigations through this study were itemized as follows,

1. Understanding of flow field and phenomena of jet mixing is the most important to design a new concept device. Especially, the shear layer deformation was necessary to get the noise benefit in all angle of engine.
2. The differences of noise benefit come from their concept of azimuthally mixing, however, both devices was able to reduce the PNL almost 1 EPNdB at 90deg.
3. An additional noise was suppressed by the Notched nozzle compared with chevron nozzle.

The author group is dealing with thrust measurement to verify thrust penalty by experimental data (hot-jet micro gas turbine) in order to make sure that the notched nozzle does not produce high thrust loss in comparison with conventional nozzle.

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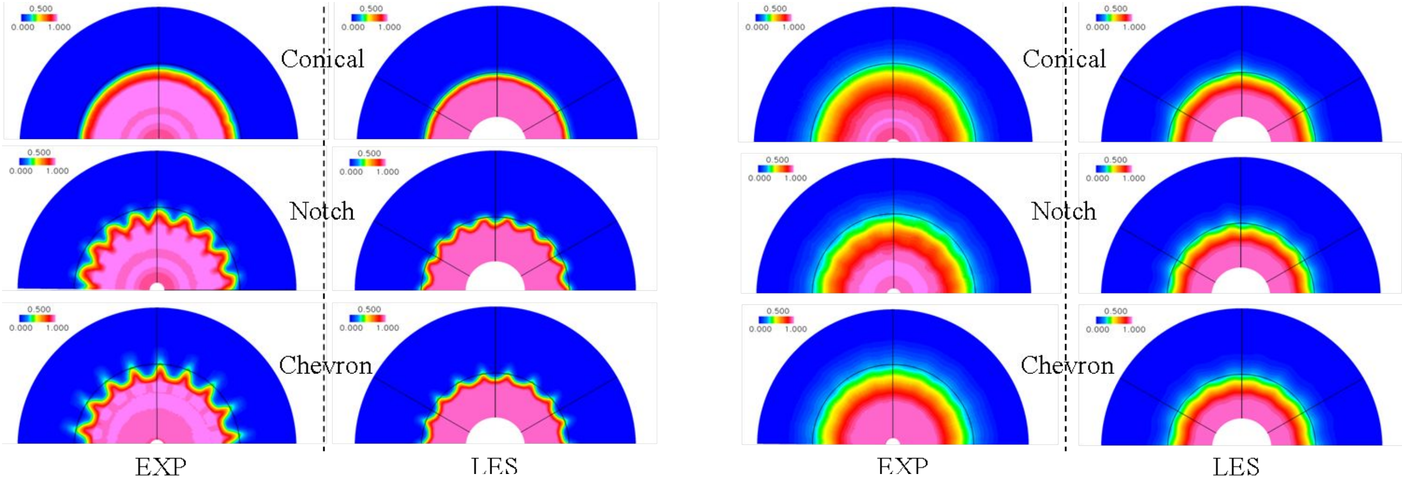


Fig.9 Total pressure distribution by pressure rake, compared with CFD data, (left) x/D=0.5, (right) x/D=2.0

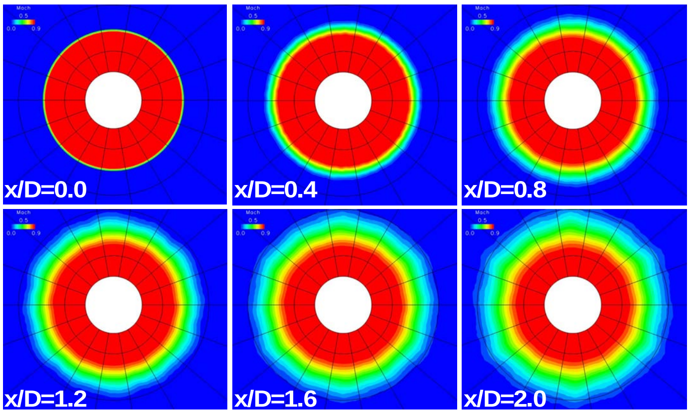


Fig.10 Mach number contours from x/D=0.0 to 2.0
Conical nozzle, me=0.9, CFD

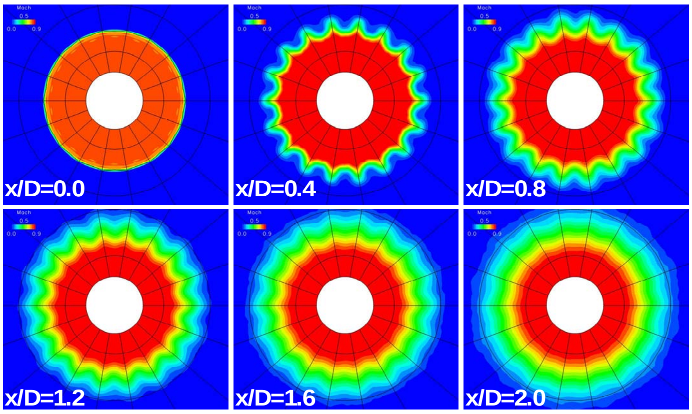


Fig.12 Mach number contours from x/D=0.0 to 2.0
Chevron nozzle, me=0.9, CFD

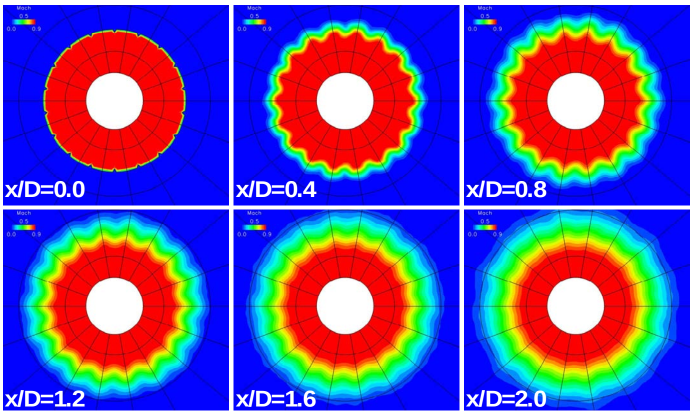


Fig.11 Mach number contours from x/D=0.0 to 2.0
Notched nozzle, me=0.9, CFD

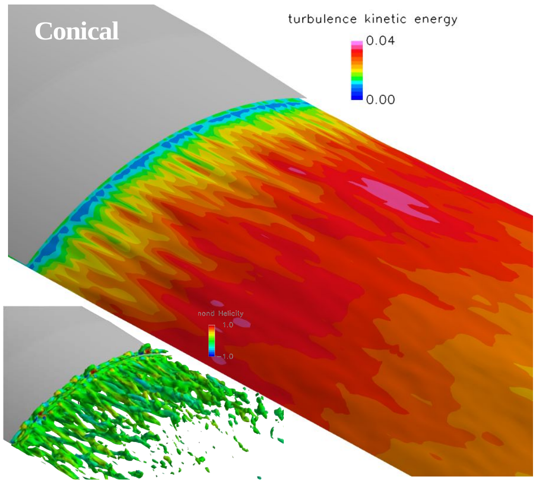


Fig.13 Schematic view of shear layer behavior for Conical
Top: Mach-surface view colored by TKE
Bottom: iso-surface at Q=2 colored by nond-helicity, CFD

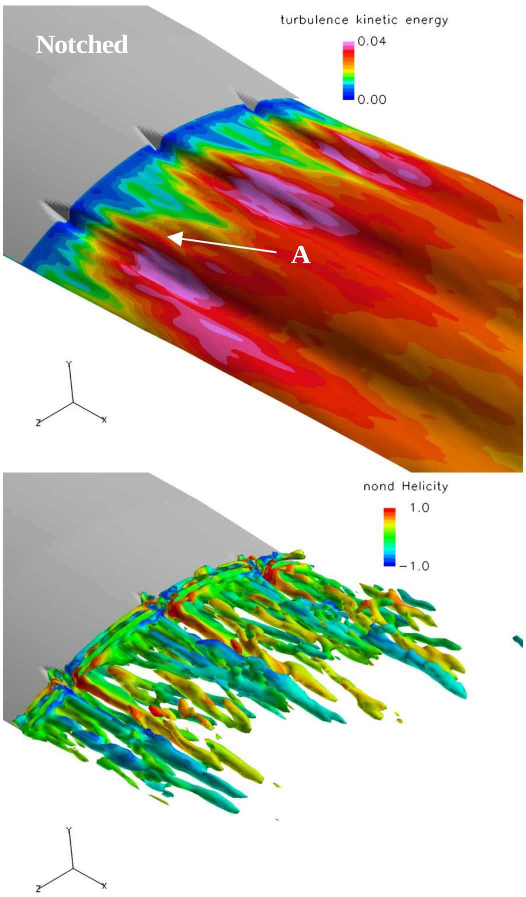


Fig.14 Schematic view of shear layer behavior for Notched
Top: mach-surface view colored by TKE
Bottom: iso-surface at Q=2 colored by nond-helicity, CFD

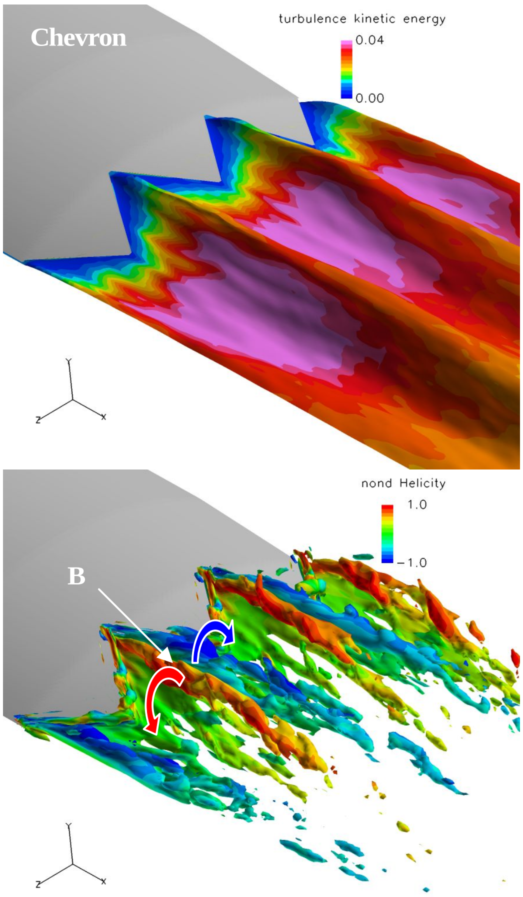


Fig.15 Schematic view of shear layer behavior for Chevron
Top: Mach-surface view colored by TKE
Bottom: Iso-surface Q=2 colored by nond-helicity, CFD

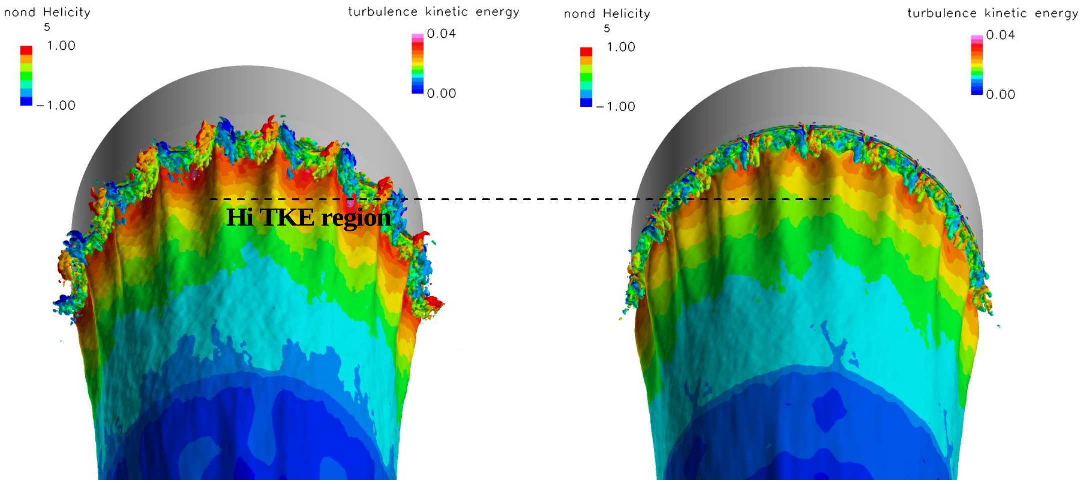


Fig.16 Jet distortion by devices from back view, CFD
Iso-surface M=0.7 Q=2, Shear layer colored by TKE
left: Chevron right: Notched

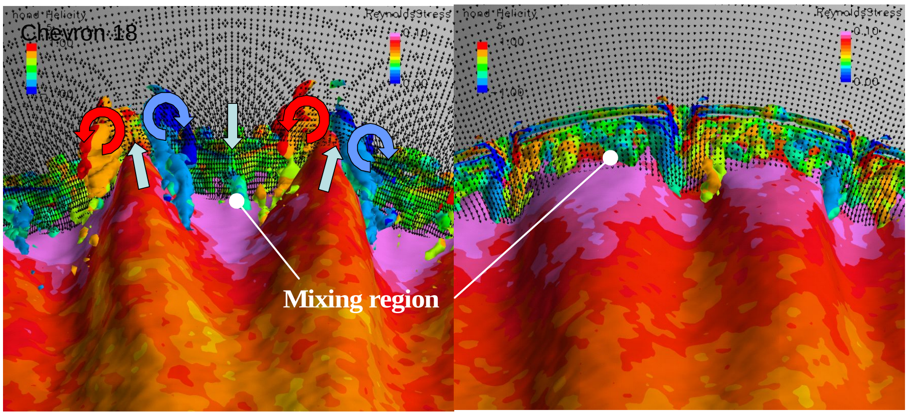


Fig.17 Schematic view of circulation at the exit
caused by devices from back view,
left: Chevron, right: Notched, CFD

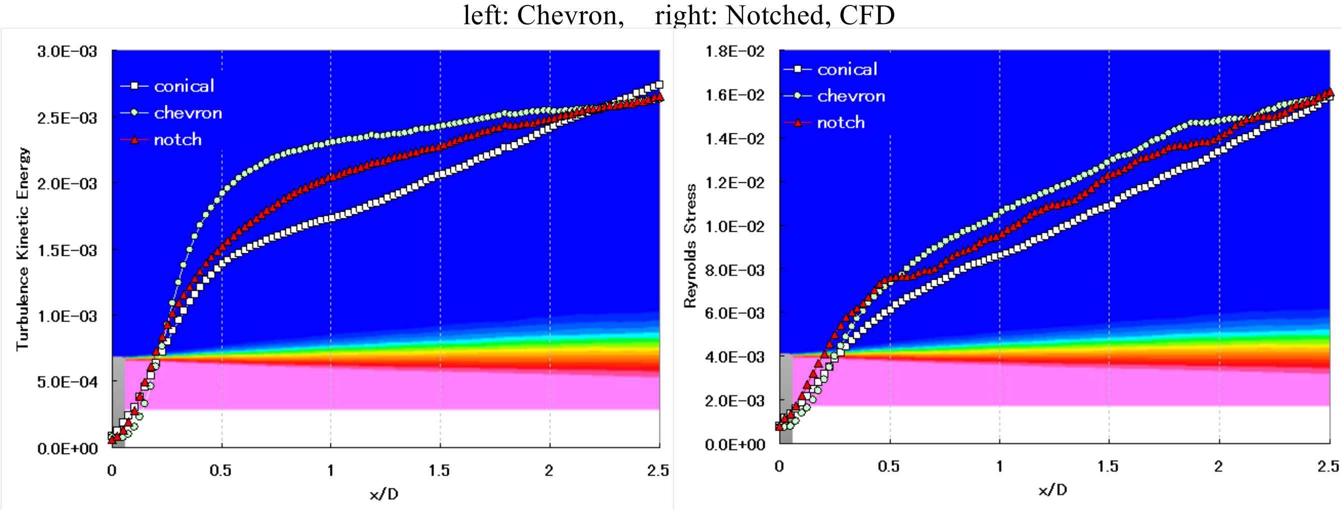
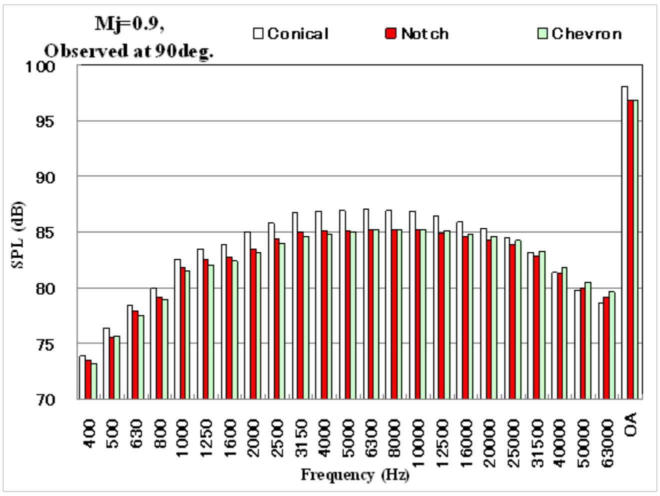
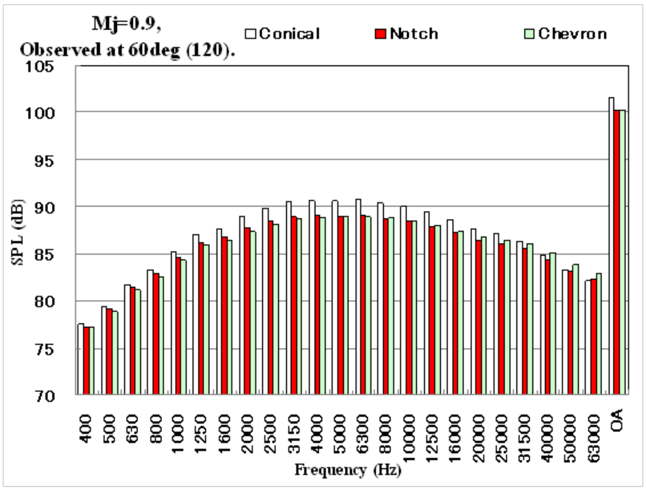


Fig.18 Time-averaged turbulence kinetic energy
and Reynolds stress from x/D=0.0 to 2.5, each
nozzle condition, CFD





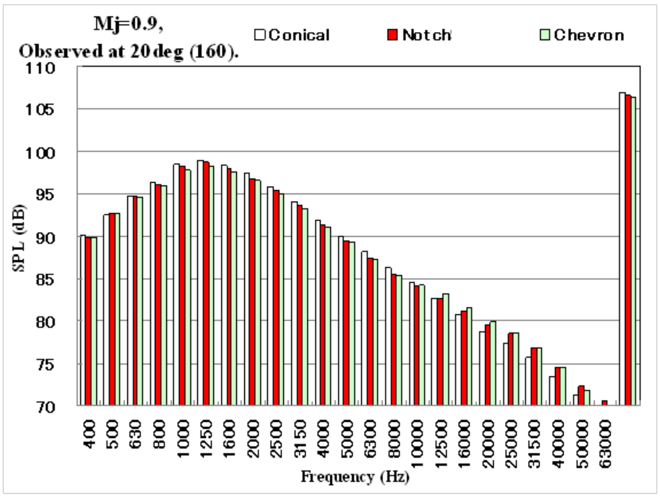


Fig.19 Far-field sound pressure level spectra, EXP
left: 90deg, right: 60deg (120deg)
btm : 20deg (160deg)

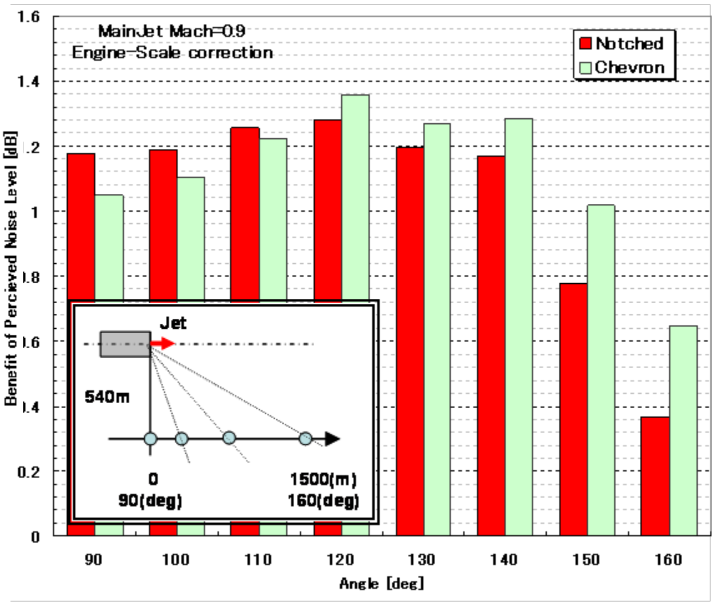


Fig.20 Perceived Noise Level Benefit, along the lateral line
for an actual engine size (400mm),
obtaining atmosphere damping, EXP