THE STUDY ON JET NOISE OF THE EXHAUST SYSTEM WITH NUMERICAL AND EXPERIMENTAL METHOD

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Because the jet flow field is transient and complex, the simple acoustic FEM is completely ineffective for the prediction of jet flow noise, and the direct numerical simulation needs a huge computation. Lighthill acoustic analogy separates the acoustic computation from fluid issues. An unsteady simulation about the jet flow of the tail pipe has been carried out, which could show the evolution of turbulence in the flow field. The equivalent noise sources have been separated from the simulation results, and then predict the sound field of the jet flow by means of Ffowcs Williams – Hawkings equation. By comparing the computational sound fields under different sound source domains, it identified the mixing and transition regions in the jet flow field, which contain the most jet noise sources. The sound field of jet noise and the sound directivity under different flow velocity are also researched by this method. The comparison between the numerical and experimental results shows the trend of simulation results is in accordance with that of experiments.

1 Instruction

The gas velocity in exhaust system would be bigger than the usual while vehicles are under high-speed or heavy load operations, then jet noise appears near the tail pipe. It would degrade the acoustic performance of the muffler, and an accurate prediction about jet noise is benefit of the exhaust system’s straight design[1-4]. But that is difficult while the generating mechanisms and propagation method of jet noise are very complicated[5], especially a contradiction exits in turbulence models between the amount and the accuracy of computations, such as DNS and RANS. Carried out an unsteady 3D simulation about low Mach number jet flow filed by mean of LES, and ensured that the big vortexes regards as areoacoustic sources have been captured, finally the response of the far field points could be obtained by FW-H equation[6, 7]. The results of simulation compared with experiment datum.

2 Numerical Simulation Model

2.1 The theory of areoacoustic

2.1.1 Large Eddy Simulation

LES is the most effective and popular turbulence model in computational fluid dynamics domain, because of the balance between the amounts of computation and the accuracy. The spatial grids are filtered by a filter function in LES model, and then the large eddies which bigger than
meshes could be resolved by Navier-Stokes equation, the else small eddies links up the former with SGS model (subgrid-scale stress). The governing equations is:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i \right) = 0
\]  

(1)

\[
\frac{\partial}{\partial t} \left( \rho u_i \right) + \frac{\partial}{\partial x_j} \left( \rho u_j u_i \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) - \frac{\partial \tau_{ij}}{\partial x_j}
\]  

(2)

Where \(\tau_{ij}\) is the subgrid-scale stress.

2.1.2 Acoustic Analogy

Acoustic analogy method decomposes the aeroacoustic issues into resolving the nonlinear near field and the linear far field\(^2\). The near field acoustic sources obtain by CFD method, and the far field can describe by FW-H equation.

\[
\frac{\partial^2}{\partial t^2} \left( H(f) \rho' \right) - c_0^2 \nabla^2 \left( \rho' \right) = \frac{\partial^2}{\partial x_i \partial x_j} \left( H(f) T_{ij} \right)
\]

\[
-\frac{\partial}{\partial x_i} \left[ \rho v_j (v_j - u_j) + p_j \frac{\partial f}{\partial x_j} \delta(f) \right]
\]

\[
+ \frac{\partial}{\partial t} \left[ \rho (v_i - u_i) + \rho_0 u_i \frac{\partial f}{\partial x_i} \delta(f) \right]
\]  

(3)

Where \(T_{ij}\) is Lighthill stress, \(\rho'\) is jump function.

There are three kind of acoustic sources in the right-hand side of equ (3), the first item is turbulence stress term, belong to quadrupole sources, the second item is dipole sources, and the last one describes monopole sources.

2.2 Fluid Computation Model

3D fluid field model was established, showed in Figure 1. Straight tube diameter \(D = 48\) mm, length is \(l = 200\) mm. Computational domain length is \(L = 20D\), width is \(W = 12D\).

![Figure 1 3D Fluid Field FEM](image)

As Figure 1 shown, hexahedrons unit was used to generate the finite element model of fluid computational domain, and local refinement meshes used in some regions where the gradient of the field quantities is big, such as orifice, the mixing and transition regions in the jet flow field, the total count of elements is about 500,000.
Environment parameters were that temperature $T_0 = 300K$, density $\rho = 1.225 \text{ kg/m}^3$, atmospheric pressure $p_0 = 101325 \text{ Pa}$. The boundary conditions of edge of flow field were pressure inlet, except that the downstream edge was set as pressure outlet. A mass flow inlet conditions was applied in the straight tube inlet, then the relation between mass flow rate $m$ and velocity inlet $v$ is shown as equ (4).

$$m = \frac{\pi \rho D^2 v}{4}$$ (4)

In unsteady CFD case, the turbulence model was LES, in which the unsteady term discretized by 2nd order implicit scheme and the convection term discretized by centred difference scheme. Time step size of unsteady simulation was $\Delta t = 1.2207 \times 10^{-4} \text{s}$. It is essential that the unsteady LES calculation needs to be run to reach a dynamically steady state, in which time variation of field quantities is almost periodic around a levelled mean value. The fluid field datum was not saved until the first 300 steps were finished.

### 2.3 Acoustic Computation Model

As Figure 2 shown, acoustical FEM was based on fluid FEM, the centre region was regard as acoustic sources, and the else was treated as propagation domain. The infinite elements were applied on the surface of whole domain for the calculation of far field. Two response points outside of the domain were settled at 500mm and 1000mm from the orifice.

![Figure 2 Acoustical FEM](image)

Two acoustical FEMs were made. As Figure 3 shown, two FEMs had the same domain size, but different sources region size. The former sources region size is $L_{\text{e1}} = 18D, W_{\text{e1}} = 10D$, another is $L_{\text{e2}} = 15D, W_{\text{e2}} = 8D$. The mesh density of two FEMs is exactly same.

![Figure 3 Acoustical FEM with different sources regions](image)
3 Results of Simulation

Simulation included the fluid computation and the acoustical computation, that the processes were reaching fluid dynamically steady state, obtaining unsteady flow field, computation of sources and computation of propagation.

3.1 Flow Field

The pressure field and velocity field while inlet velocity is 60m/s were shown in Figure 4.

![Figure 4 Transient Flow Field (v=60m/s)](a) Pressure  (b) Velocity

3.2 Sound Field

3.2.1 Acoustic Sources

The acoustic sources obtained from fluid field were shown in Figure 5. The shape of sources density was just the same as fluid field, and the intensity of the sources was decreasing while the frequency was increasing.

![Figure 5 Lighthill Sources Density (60m/s)](a) 100Hz  (b) 500Hz  (c) 1000Hz

By using FW-H equation, the sound field had been calculated. As Figure 6 shown, the low frequency noise appeared around the most areas, and the middle-high frequency noise distributed in the mix and transition regions in the jet flow field mostly. The latter’s intensity is weaker than the former.
3.2.2 Far Field

The response of far field was calculated by infinite element method. The responses of two field points that were settled as section 2.3 were obtained under different velocities. The octave spectrums were shown in Figure 7. It suggested that the jet noise of low Mach number fluid was dominated by low frequency noise, which has the same characters with acoustical sources. Near from the orifice, the intensity of low frequency increased with increasing of the velocity, while the changes of the middle-high frequency’s intensity were not obvious. A little away from the orifice, the jet noise level just increased with the increasing of the velocity.

3.2.3 Comparison of Acoustic Sources Regions

With different acoustic sources regions, the response of two field points remains unchanged, just as Figure 8 showed. It seemed that only the mix and transition regions were necessary for the sources region.
4 Experiment

An experiment was carried out with a cold air flow bench, and the microphone installed 1000mm away from the orifice. The spectrums under various velocities were shown in Figure 9. It appeared that the trend of simulation results is accord with that of the experimental, but the difference of levels is big.

5 Conclusions

(1) Both the simulation and the experiment show that low frequency noise dominates the jet noise of low Mach number flow.

(2) Near from the orifice, the intensity of low frequency increases with increasing of the velocity, while the changes of the middle-high frequency’s intensity are not obvious. A little away from the orifice, the jet noise level just increases with the increasing of the velocity.

(3) Only the mix and transition regions were necessary for the sources region.

REFERENCES


