# 非定常超音速円形ジェットの数値解析

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## Numerical Simulation of Unsteady Supersonic Circular Jet

by

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ABSTRACT

Time evolution of unsteady supersonic circular jet is investigated numerically by using a TVD finite difference scheme for the Euler equations. It is shown that the supersonic jet injected into an ambient air is unstable and rapidly evolves into turbulent field. The Kelvin-Helmholtz instability along slip lines downstream of the triple points of shocks is responsible for generation of the second vortices which are convected along the outer boundary of the first vortex. The numerical results are compared with the experiments and a good agreement is obtained between them.

## INTRODUCTION

Unsteady supersonic jets have been used in many research fields and also realized in many practical applications. For example, at the lift-off of a rocket, supersonic jets are exhausted from nozzles just after the ignition. At the operation of an air bag for a car driver, an unsteady supersonic jet is used. Furthermore it has been recognized that pulsed supersonic jets provide effective means to control the chemical energy release in variety of combustion system -as utilized in advanced concepts for internal combustion engines.[1] In light of such a situation it is crucially important to investigate characteristics of unsteady flow behavior of supersonic jets.

The early stage of a jet evolution is well known as a diffraction phenomenon of shock wave around a corner, which has been investigated for long time by many researchers.[2] Somewhat later, the second shocks are generated in the flow field and connected to each other at the jet axis to form a single shock with an arc shape.[3),4] In the middle stage, a shock cell structure is constructed and a slip surface is generated downstream of the triple point of the shock waves. This surface is very kelvin-Helmholtz unstable and is responsible for generation of the second vortices. In the later stage, a quasi-steady jet is constructed near the open end and initiates its self-sustained oscillation and a special kind of instability called "screech" occurs.[5),6]

In the present paper, an unsteady supersonic circular jet is treated numerically. Focus is placed on the jet evolution in the middle and later stages. The Kelvin-Helmholtz instability and generation of the second vortices are investigated in detail. The origin of asymmetric behavior of the jet is also investigated. It will be made clear that the Kelvin-Helmholtz instability along the slip surface plays a very important role in the jet instability and its asymmetric behavior. The numerical results are compared with experiments and a good agreement is obtained between them.

## NUMERICAL ANALYSIS

Numerical simulations were performed on a supercomputer Fijitsu VP-2600 at the Data Processing Center of Kyoto University. Euler equations for an axially symmetric flow were solved by a finite-difference TVD scheme.[7] The mesh number is 400×400 and there are 40 meshes in the nozzle exit plane. The jet conditions at the nozzle exit are $M_j$=1.02, $p_j/p_\infty$

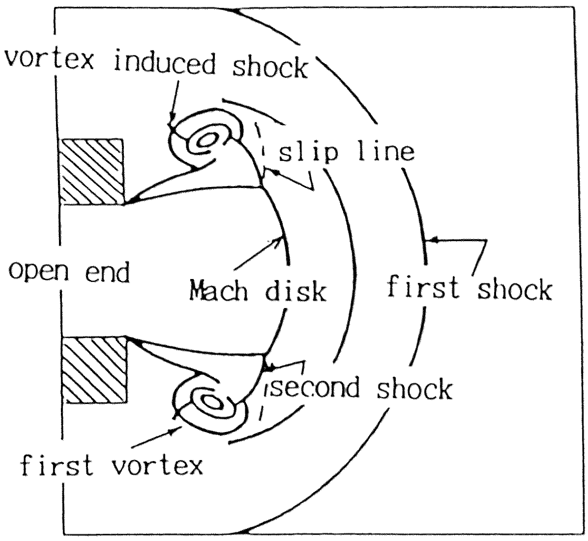



Fig.1 Flow characteristics of unsteady supersonic circular jet.

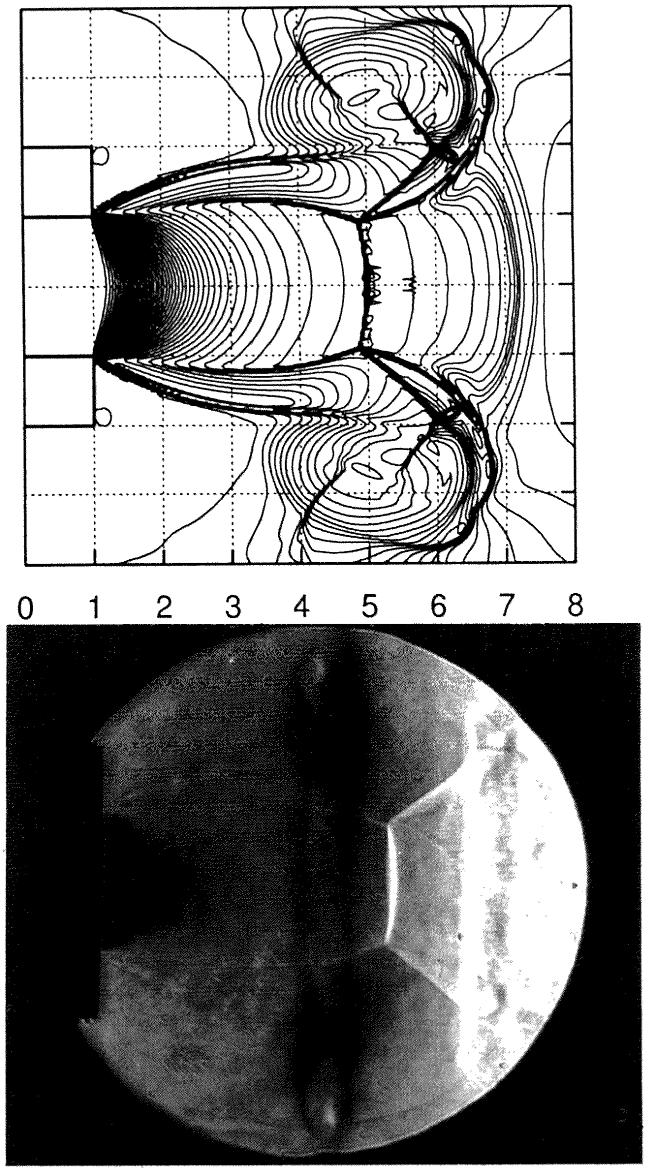



Fig.2 Density contours of unsteady jet at t = 224 $\mu$sec and the corresponding schlieren photograph.

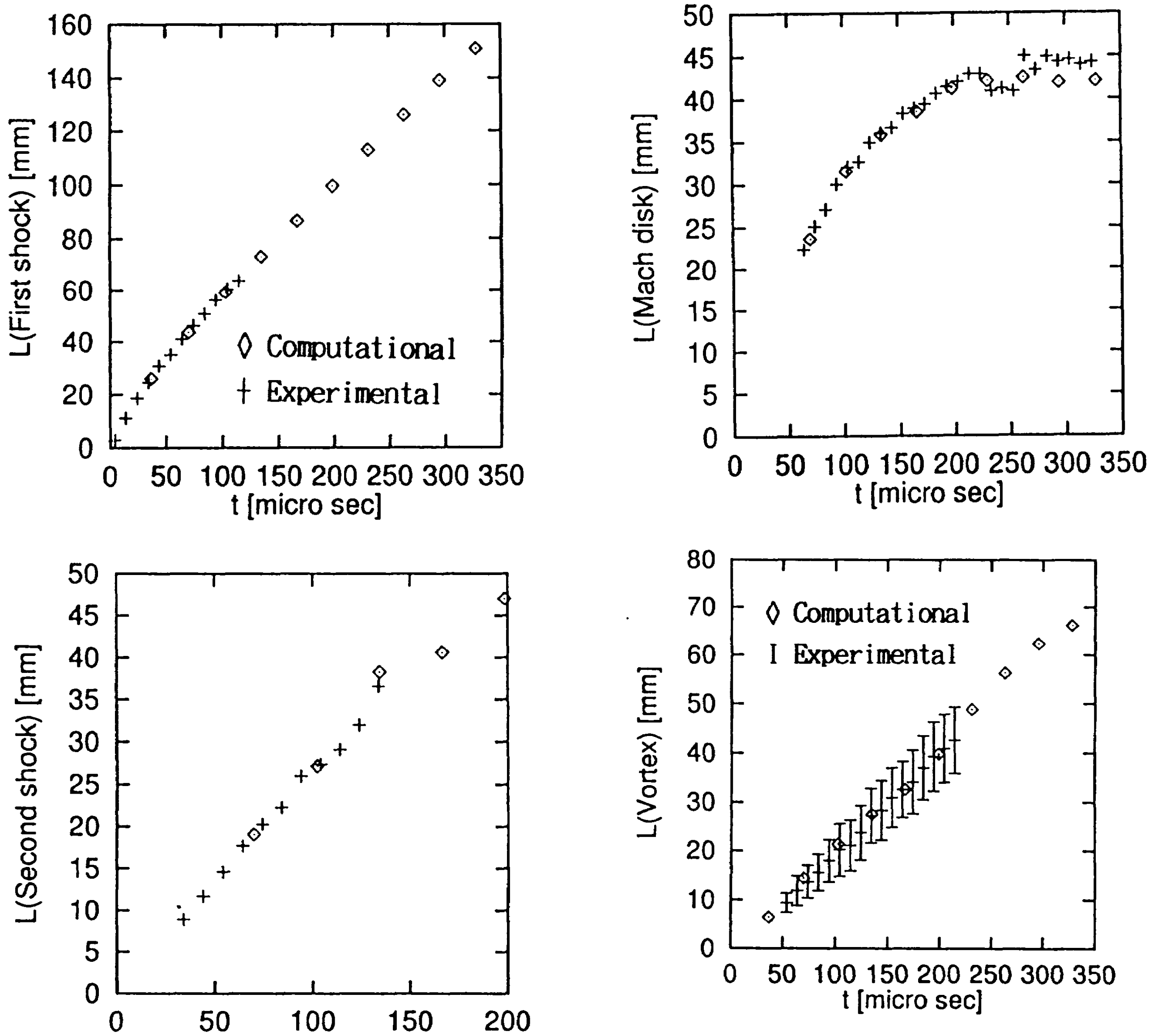
$= 5.0$, $\rho_j/\rho_\infty = 2.8$, where M, p and $\rho$ are the Mach number, the gas pressure and the gas density and the subscripts j and $\infty$ denote the jet and ambient gas conditions, respectively.

Flow characteristics of an unsteady supersonic jet are shown in Fig. 1. A sample of density contours is shown in Fig.2, where the corresponding shlieren photograph is also shown for comparison. Numerical results can well explain the time evolution of the jet. The experiments and the numerical results are compared more in detail in Fig. 3, where the distances are measured from the nozzle exit plane to the first shock (main shock), the second shock, the third shock (vortex induced shock), the Mach disk and the first vortex, respectively. The agreement between them is very well. Only the difference between the numerical and the experimental results exists in the location of the second vortices. This disagreement will come form the fact that the effect of gas viscosity cannot be neglected for the behavior of the second vortices. However, qualitatively, both results agree very well.

The Kelvin-Helmholtz roll-up is simulated as shown in Fig. 4 and the corresponding shlieren photographs are shown in Fig. 5. The outer part of the second shock splits into two parts. One is the reflected shock and another is the shock in the first vortex which propagates upstream through the first vortex. At this stage, strong pressure waves are produced by interactions between the vortices and also between the vortex and the shock. Some part of these pressure waves propagate upstream and stimulate the very unstable jet boundary to produce disturbances of the shock cell structure.

At least numerically or theoretically, it will be reasonable to expect that the stable flow field cannot be obtained. Experimentally it is confirmed that a quasi-steady underexpanded supersonic jet experiences a self-sustained oscillation and propagates a very strong sound wave named "screech". In this respect,the present numerical results will be at least qualitatively consistent.

Finally it has to be emphasized that experimentally the flow field of an unsteady supersonic circular jet is strictly not axially symmetric. The first ringed vortex is unstable and just after its generation it begins to



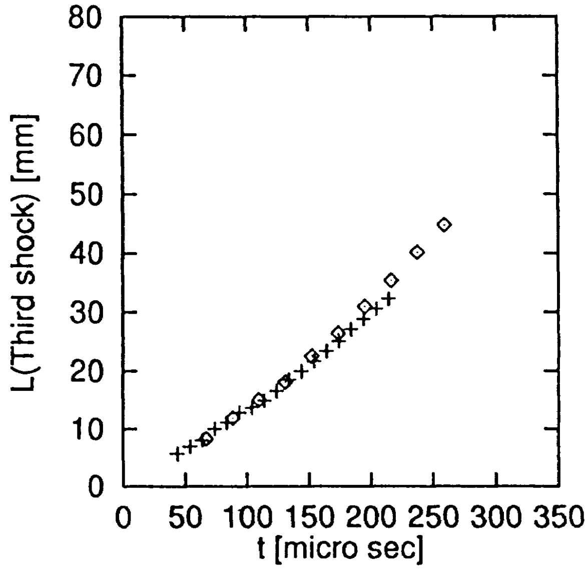




Fig.3 Comparison between numerical and experimental results.

show some asymmetric behaviour. In the photographs, it can be well seen that the second shock in the first vortex is not axially symmetric. It can also be confirmed that the second vortices are not completely axially symmetric. It is well known that the quasi-steady supersonic round jet for $p_j/p_\infty$ = 5 oscillates in a flattering mode which is not symmetric. Perhaps the previous asymmetric flow behaviour will be responsible for a self-sustained oscillation in the flattering mode of the quasi-steady jet.

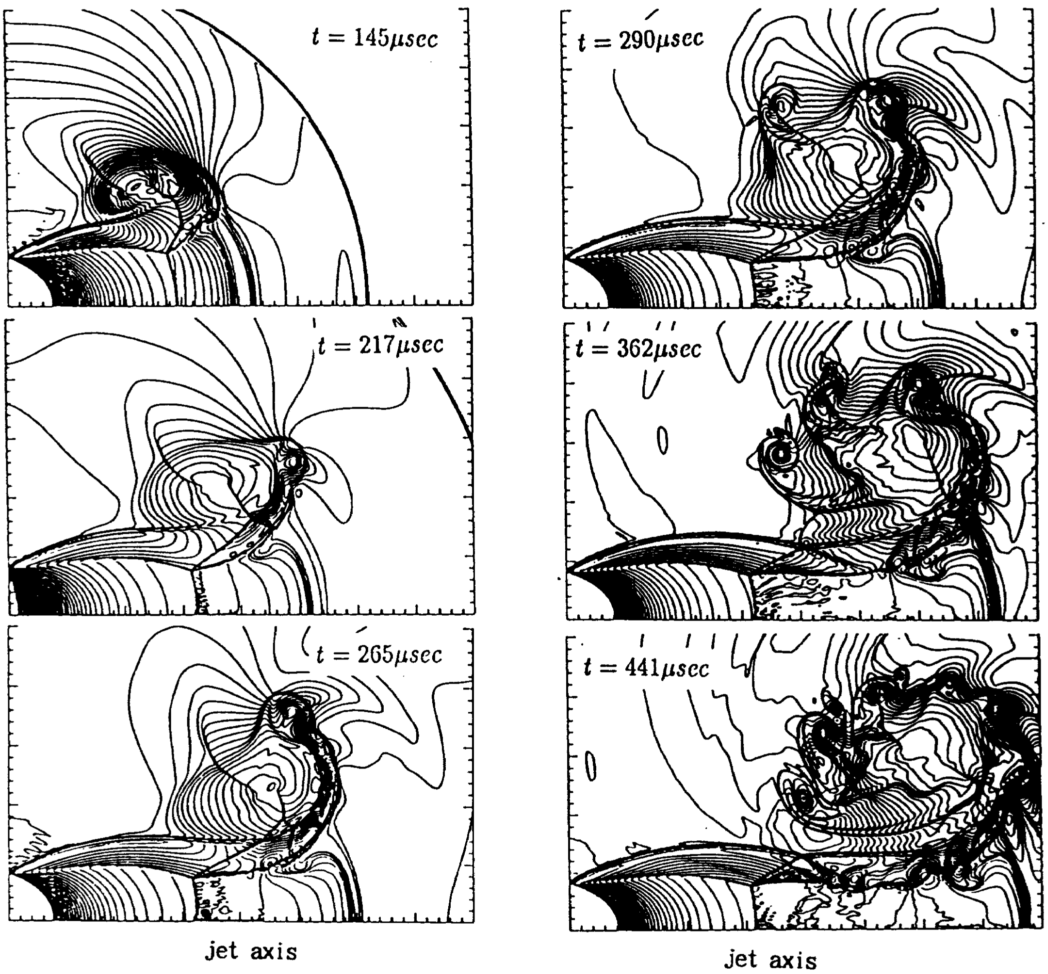



Fig.4 Numerical simulation of Kelvin-Helmholtz roll-up.

CONCLUSIONS

An unsteady supersonic circular jet was investigated numerically. The experiments demonstrate that a supersonic jet injected into an ambient air is unstable and rapidly evolve into turbulent field, which is quite consistent with the present results. In this transition, the Kelvin-Helmholtz instability along the slip lines downstream of the triple points of the shock-cell plays a very important role, which suggests that the presence of the shock-cell structure in the supersonic jet is responsible for enhanced instability of the flow field and effective mixing of the gas. The experiments and the numerical simulations agreed very well at least in the early and middle stages of the jet evolution.

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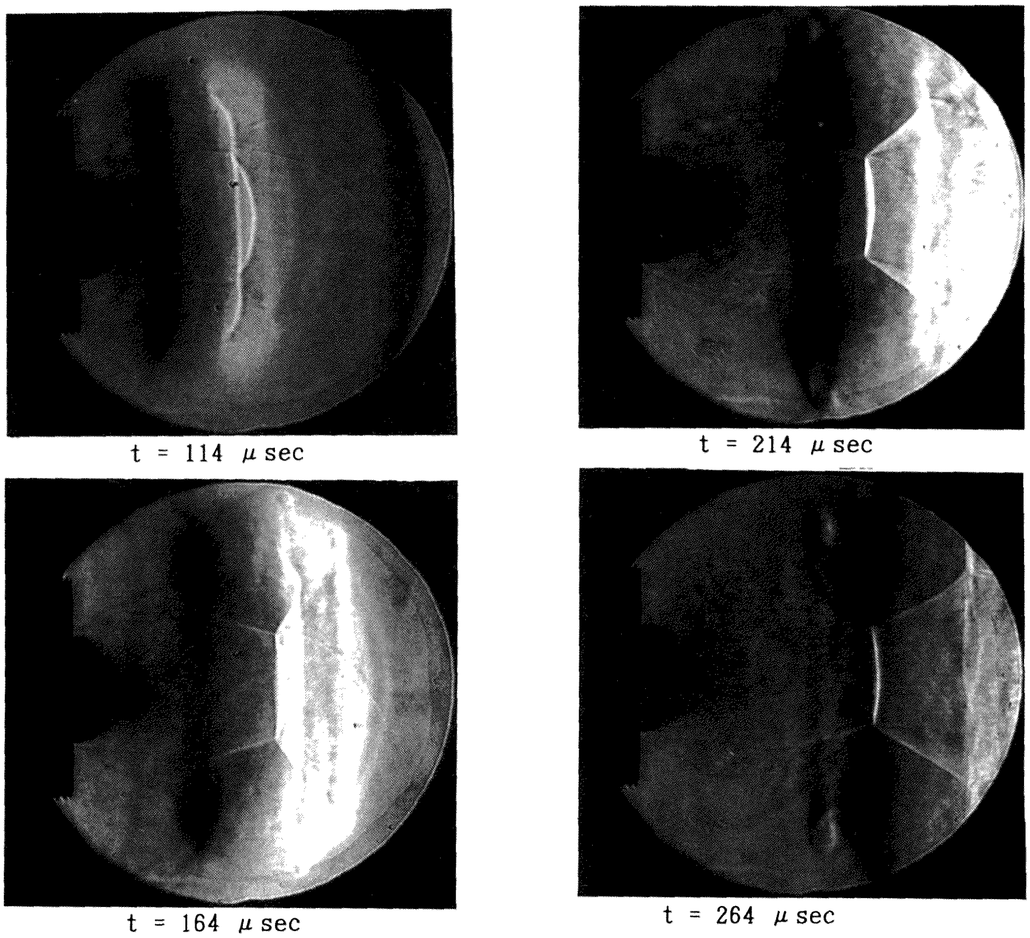


Fig.5 Schlieren photographs of second vortices.