EXPERIMENTAL STUDY ON SELF-INDUCED EXCITATION PHENOMENA OF OPPOSING JET IN SUPERSONIC FLOW

K. Karashima
Department of Mechanical Engineering, Nishinippon Institute of Technology, Japan
S. Aso and G. Takami
Department of Aeronautics and Astronautics, Kyushu University, Japan
K. Sato
ISAS, Japan

Keywords: *Supersonic flows, Opposing jets, Shock waves*

Abstract

The self-induced oscillations in supersonic opposing jet to supersonic free stream have been investigated. In opposing jet flows in supersonic flows the flow fields have stable region and unstable region, depending on the ratio of total pressure of free stream to total pressure of opposing jet. In the present study the ratio of total pressure of free stream to total pressure of opposing jet , P_{0j}/P_0, *are selected as 0.469, 0.655, 0.984 and 1.51 . Free stream Mach number and opposing jet Mach number are 2.5 and 1.5 respectively. The experimental model consists of semi-spherical nose and cylindrical body. The flow fields are visualized by the Schlieren technique and recorded by high speed video camera. Also pressure fluctuations on the model surface are measured. The results show that there are two features in self-induced shock wave oscillations and bow shock wave oscillation is observed in lower total pressure ratio and recompression shock wave oscillation is observed in higher total pressure ratio. Also the peak frequencies for both cases are different. The pressure time history and instantaneous flow pattern show good correlations. The global properties of self-indeuced shock wave oscillation of opposing jets in supersonic flows have been revealed.*

Nomenclature

D	Diameter of jet-nozzle exit [mm]
M_∞	Free stream Mach number
M_j	Mach number of opposing jet
P	Static pressure [Pa]
P_{0j}	Jet-plenum stagnation pressure [Pa]
P_0	Free-stream stagnation pressure [Pa]
Re	Reynolds number

Subscript

j	Opposing jet
0	stagnation condition
2	condition after normal shock wave in supersonic free stream

1 Introduction

The supersonic opposing jet to supersonic free stream has been considered to be useful to reduce the pressure distribution on the body surface or the surface aerodynamic heating loads. However, when the supersonic opposing jet is applied into supersonic free stream, the interaction of self-induced oscillations in supersonic opposing jet to supersonic free stream occurs and the interaction problem has been one of the most difficult problems on unsteady supersonic flow. There are many researches on those interacting flow fields [1]-[22].

Also recently various types of space transportation systems have been proposed and

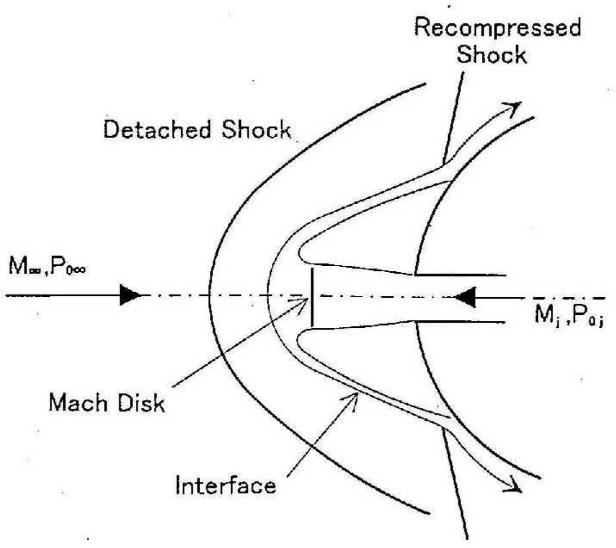


Fig.1 Schematic diagram of the flow field

the developments of some of space transportation systems are in progress. One of the promising space transportation systems is vertical take-off and landing space transportation system such as DC-X projects in United Staed. The transportation system is nominated one of the Single-Stage-To-Orbit space transportation systems. In the operation in return phase to the ground the vehicle uses the opposing jet to reduce the descending speed. In this situation supersonic opposing jet is applied into supersonic free stream from the bottom surface of the vehicle and interacts with supersonic free stream as shown in Fig. 1. The opposing jet generates the detached shock wave and recirculating region on the bottom surface.

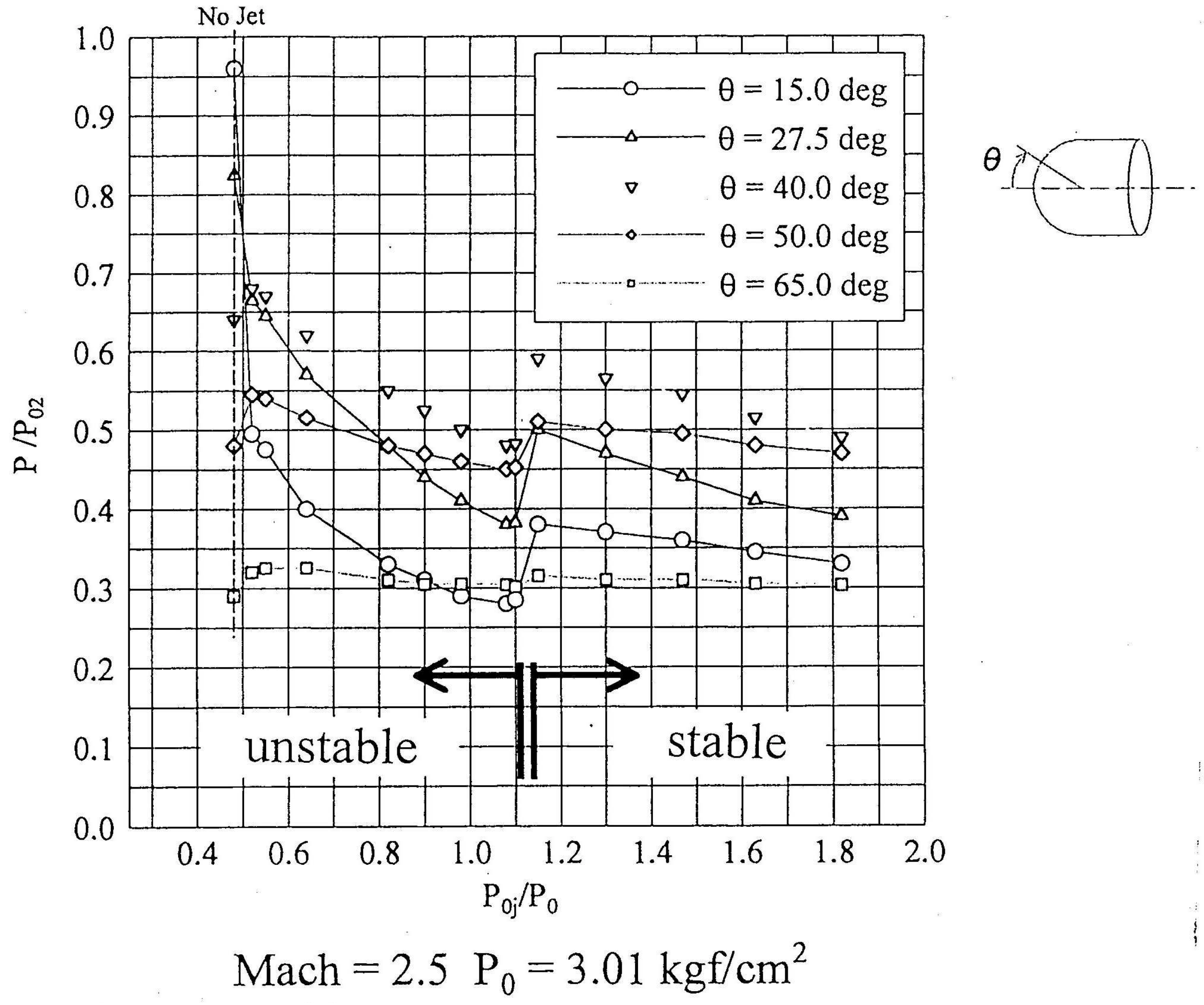


Fig.2 Relation between surface pressure and total pressure of the opposing jet[22]

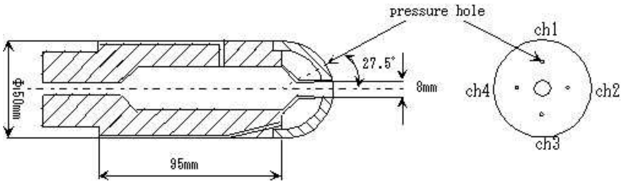


Fig.3 Schematic diagram of model

In those situation detached shock wave oscillates when total pressure ratio, P_{0j}/P_0, is small. Those phenomena are understood as self-induced oscillations in supersonic opposing jet to supersonic free stream.

In the present study the self-induced oscillations in supersonic opposing jet to supersonic free stream have been investigated. In opposing jet flows in supersonic flows the flow fields have stable region and unstable region, depending on the ratio of total pressure of free stream to total pressure of opposing jet as shown in Fig. 2. In the present study the ratio of total pressure of free stream to total pressure of opposing jet , $P_{0j}/P_{0,}$ are selected as 0.475, 0.658, 0.910 and 1.507. Free stream Mach number and opposing jet Mach number are 2.5 and 1.5 respectively. The experimental model consists of semi-spherical nose and cylindrical body. The flow fields are visualized by the Schlieren technique and recorded by high speed video camera. Also pressure fluctuations on the model surface are measured. The results show that there are two features in self-induced shock wave oscillations and bow shock wave oscillation is observed in lower total pressure ratio and recompression shock wave oscillation is observed in higher total pressure ratio. Also the peak frequencies for both cases are different. This also relates different unsteady properties and flow physics of self-induced shock wave excitation. The pressure time history and instantaneous flow picture show good correlations. The global properties of self-indeuced shock wave oscillation of opposing jets in supersonic flows have been revealed.

2 Experimental apparatus and procedures

2.1 Experimental model and wind tunnel

The model, which is used in the present experiments, is shown in Fig. 3. The diameter of the model is 50 mm. The nose region is a semi-sphere followed by circular cylinder. In the center axis a conical nozzle, whose exit Mach number is 1.5 and throat diameter is 5 mm, is set at the top of the model. The pressure holes are prepared on the surface of the model. The location of the pressure hole is indicated by the angle, θ, measured from the center axis. In the present experiments θ is selected as 27.5 degrees. The four pressure holes are prepared on the model surface. Each hole is loacated at the same angle from the top of the model with θ of 27.5 degrees and 90 degrees difference apart along circumferential line.

The supersonic wind tunnel of ISAS (The Institute of Space and Astronautical Science) is used in the present experiments. The test section is 600 mm by 600 mm. The free stream Mach number can be changeable from 1.5 through 4.0. The model is set in the wind tunnel and compressed air is supplied from the outside pressure reservor to obtain the opposing jet through pressure settling equipment. The surface pressure fluctuations are measured by using high frequency response pressure sensors. Also for the flow visualization conventional Schlieren technique is used. The flow field are recorded by using high speed digital video camera, whose top sampling rate is 24.7 μsec.

2.2 Testing conditions and procedures

In the present study free steam Mach number is kept as 2.5 and opposing jet mach number is kept as 1.5. The ratio of total pressure of free stream to total pressure of opposing jet , $P_{0j}/P_{0,}$ are selected as 0.475, 0.658, 0.910 and 1.507.

case	M.	M_j	P_{0j}/P_0	Re
A	0.0	0.0		
B	2.5	0.0	0.475	$1.64x10^6$
C	2.5	1.5	0.658	$1.64x10^6$
D	2.5	1.5	0.910	$1.65x10^6$
E	2.5	1.5	1.507	$1.65x10^6$

Table-1 Testing condition

The testing condition is shown in Table-1.

In the Table case A is no wind with no jet and case B is wind with no jet. Those cases are selected to obtain signal noise level and surface pressure fluctuations without opposing jet.

In the table Case C is selected to observe unstable condition of the flow field. Case D is selected to observe quite unstable condition.

Case E is selected to observe stable condition of the detached shock wave and unsteady condition of recompression shock wave on the body surface.

3 Experimental Results and discussion

3.1 Flow visualization

The representative flow patterns are shown in Fig. 4. The supersonic flow without opposing jet is shown in Case B. The detached shock wave is very clear and stable. In cases of C and D detached shock wave is invisible. The results show the detached shock wave is oscillating back and forth to the free stream. In case E detached shock wave is clear and recompression shock wave is invisible. The results show the recompression shock wave is oscillating in the recirculating region.

3.2 Pressure fluctuations and spectrum of fluctuating pressure

The temporal pressure fluctuations for Cases of B, C, D and E are shown in Fig. 5. In case B of no opposing jet pressure fluctuations are quite small. However, in cases of C, D and E pressure fluctuations are quite large. Those are due to oscillating detached shock wave or

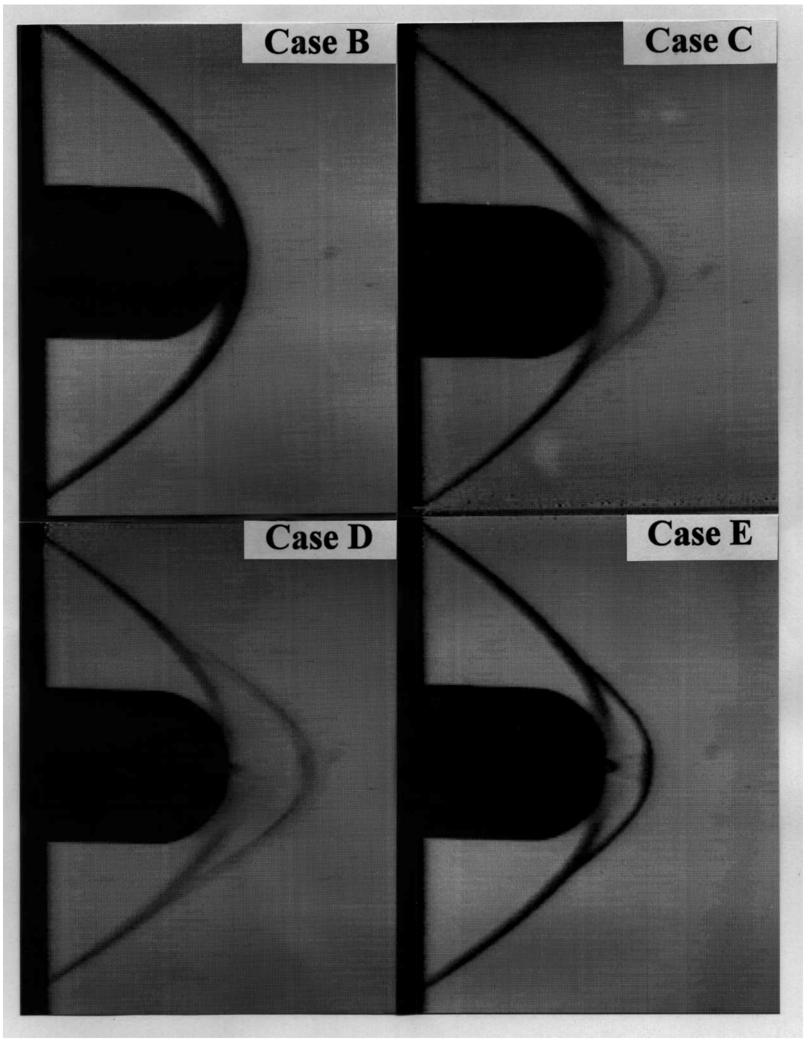
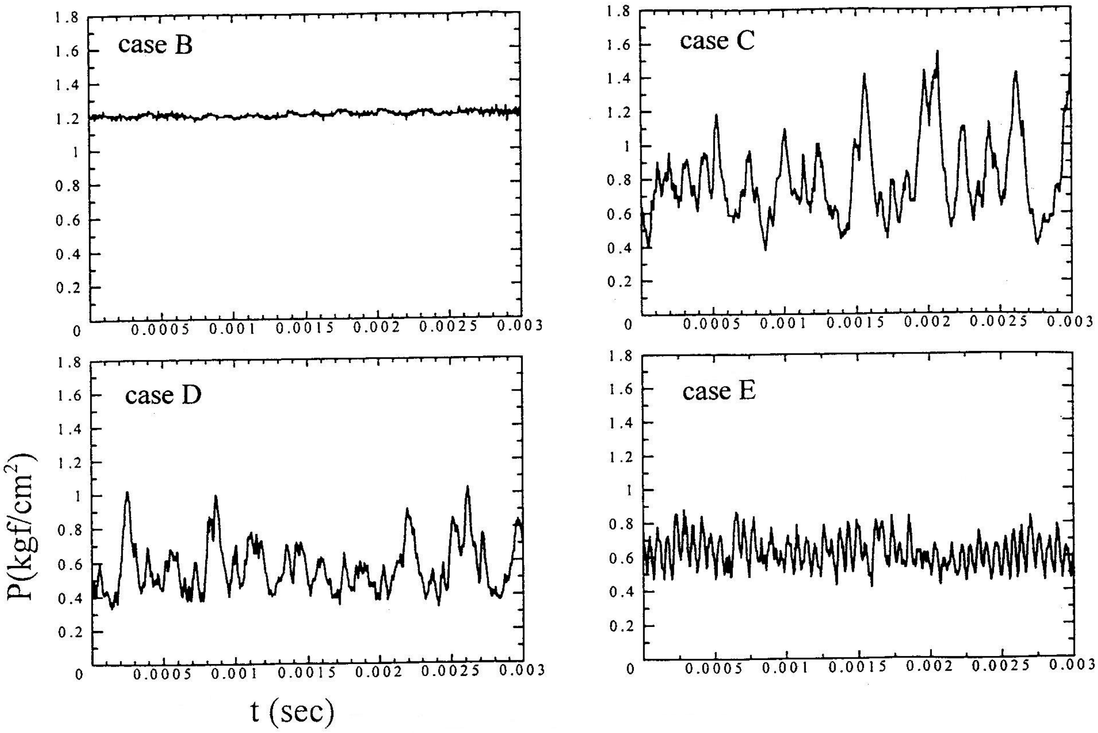


Fig.4 Representative flow patterns



s

Fig.5 Temporal pressure fluctuation

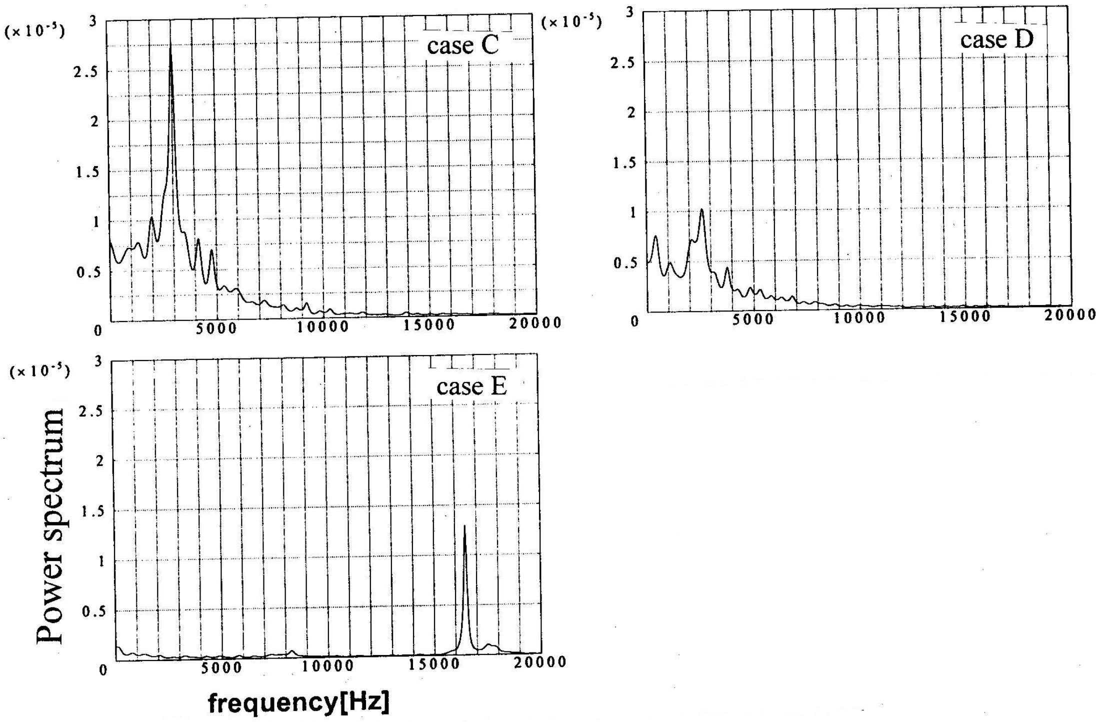


Fig.6 Spectrum diagram of the pressure fluctuations

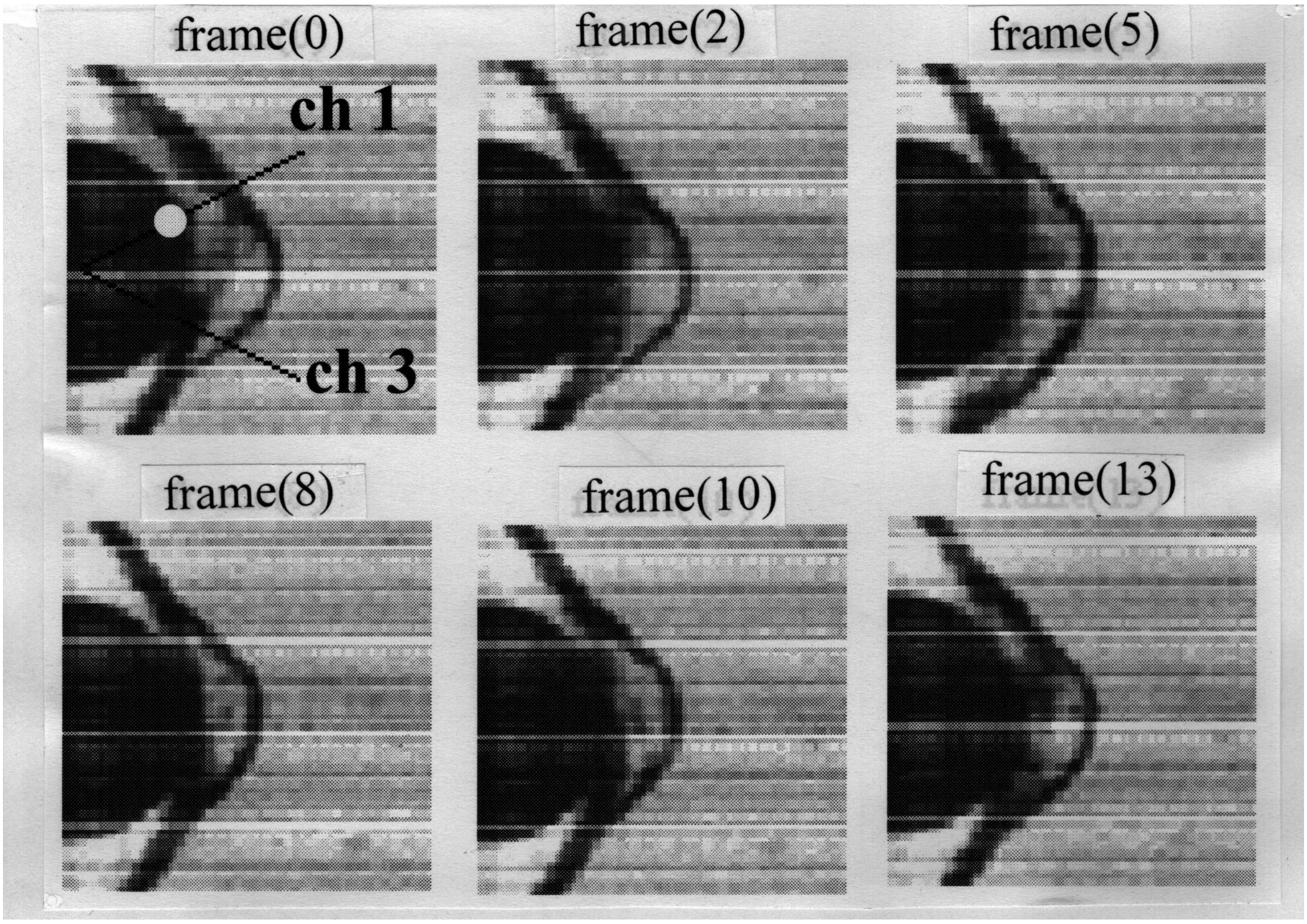


Fig.7 Instantaneous pressure time histories of case C at four pressure holes and the two temporal pressure histories of channel 1 and 3, which are separated 180 degrees in circumferential location

recompression shock wave. Also the temporal pressure history show moderate high frequency compared with case B for cases C and D and quite high frequency compared for case E. For the amplitude of the pressure fluctuation the amplitudes of case C and D is larger than the amplitude of case E. Those properties are quite clear after conducting spectrum analysis. The results are shown in Fig. 6. In cases of C and D peak frequencies are 2993 and 2435 Hz. However, in case E peak frequency is 16505 Hz. The results show that oscillating detached shock wave generates moderate higher frequency pressure fluctuations and larger amplitude of the pressure fluctuations on the model surface. On the other hand oscillating recompression shock wave generates higher frequency pressure fluctuations and smaller amplitude of the pressure fluctuations on the model surface.

The instantaneous pressure time histories of case C at four pressure holes, whose circumferential locations are 90 degrees apart and apex angles are 27.5 degrees all tother, are shown in Fig. 7. The two temporal pressure histories, which are separated 180 degrees in location of the same circumferential location, show 180 degrees phase lag. Also the results show that there is some circumferential movement of the detached shock wave. The series of instantaneous Schlieren pictures of case C for the same condition are shown in Fig. 8. Each frame number is indicated in the Fig. 7. The results show the maximum pressure is observed when the detached shock wave is closer to the model surface and the minimum pressure is observed when the detached shock wave is far from the model surface.

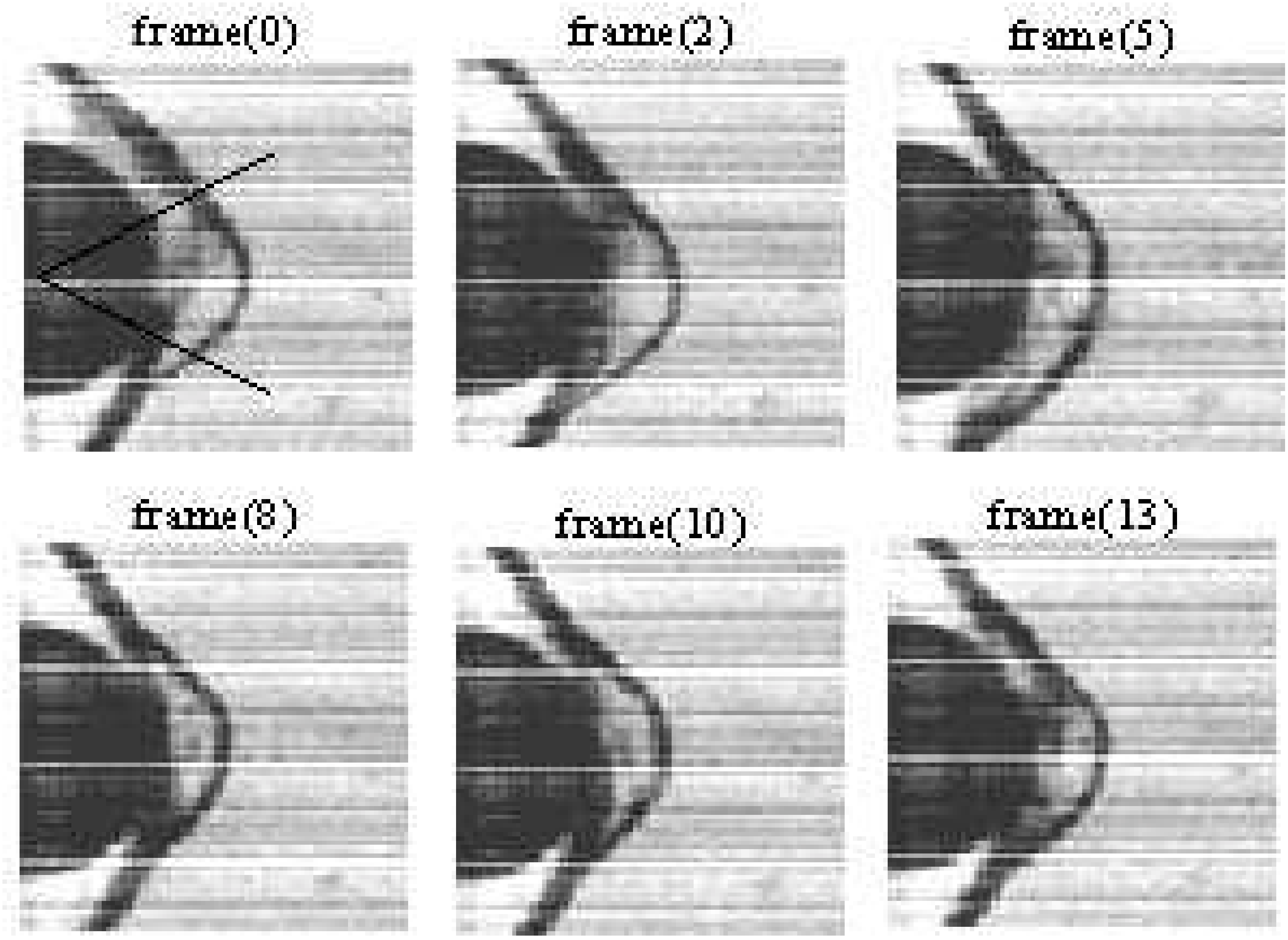


Fig.8 Series of instantaneous Schlieren pictures of case C for the same condition (24.7 μsec/frame)

4 Conclusions

Self-induced shoch wave oscillations phenomena in supersonic opposing jet to supersonic free stream are investigated in the present study. In the present study unstable flow conditions are selected and the flow fields are visualized by the Schlieren technique and recorded by high speed video camera. Also pressure fluctuations on the model surface are measured.

The results show that there are two features in self-induced shock wave oscillations and bow shock wave oscillation is observed in lower total pressure ratio and recompression shock wave oscillation is observed in higher total pressure ratio. The peak frequencies for both cases are different. This also relates different unsteady properties and flow physics of self-induced shock wave excitation. The global properties of self-indeuced shock wave oscillation of opposing jets in supersonic flows have been revealed.

References

[1] Laptoff, M. Wingflow Study of Pressure Drag Reduction at Transonic Speed by Projecting a jet from the Nose of a Prolate Spheroid of Fineness ratio 6. NACA RM No. L51E09, 1951

[2] Watts, G. A. An Experimental Investigation of Sonic Jet Directed Upstream Against a Uniform Supersonic Flow. UTIA TN No. 7, 1956.

[3] Love, S. E. The Effect of a Small jet of Air Exhausting from the Nose of a Body of Revolution in Supersonic Flow. NACA RM No. L52119a, 1952.

[4] Love, E. S. A Re-examination of the Use of Simple Concepts for Predicting the Shape and Location of Detached Shock Wave. NACA TN No. 4170, 1957.

[5] Stalder, J. R. and Inouye, M. A Method of Reducing Heat Transfer to Blunt Bodies dy Air Injection. NACA RM No. A56B27a, 1956.

[6] Mcmahon, H. M. An Experimental Study of Mass Injection at the Stagnation Point of a Blunt Body. GALCIT Hypersonic Project Memo. No. 42, 1958.

[7] Warren, C. H. E. An Experimental Investigation of the Effect of Ejecting a Coolant Gas at the Nose of a Bluff Body. Jour. Fluid Mech. Vol. 8, 1960.

[8] Baron, J. R. and Alzner, E. An Experimental Investigation of a Two-Layer Shock Cap due to Blunt Body Nose Injection. Jour. Fluid Mech. Vol. 15, 1963.

[9] Gollnick, Jr. A. F. Blunt Body Experiments with Central Injection. AIAA Jour. Vol. 4, 1966.

[10] Charczenko, N. and Hennessy, K. W. Investigation of a Retrorocket Exhausting from the Nose of a Blunt Body into a Supersonic Free Stream. NASA TN D-751, 1961.

[11] Hayman, Jr. L. O. and McDearmon, K. W. Jet Effects on Cylindrical Afterbodies Housing Sonic and Supersonic Nozzles Which Exhaust Against a Supersonic Stream at Attack from 90° to 180° NASA TN D-1016, 1962.

[12] Romeo, D. J. and Sterrett, J. R. Exploratory Investigation of the Effect of a Forward-Facing Jet on the Bow Shock of a Blunt Body in a Mach number of 6 Free Stream. NASA TN D-1605, 1963.

[13] Romeo, D. J. and Sterrett, J. R. flow Field for Sonic Jet Exhausting Contour to a Hypersonic Main Stream. AIAA Jour. Vol. 3, 1965.

[14] Adamson, T. C. and Nicholls, J. A. On the Structure of Jets Exhausting Contour to a Hypersonic main Stream, AIAA J., Vol. 3, 1965.

[15] Love, E.S. et. al. Experimental and Theoretical Studies of Axisymmetric Free Jets, NASA TR No. 6, 1959.

[16] Barbar, Jr. E.A. An Experimental Investigation of Stagnation Point Injection, J. Spacecraft, Vol. 2, 1965.

[17] Fineley, P.J. The Flow of a Jet from a Body Opposing a Supersonic Free Stream, J. Fluid Mech., Vol. 26, 1965.

[18] Peterson, V.L. and McKenzie, R.L. Effect of Simulated Retrorockets on the Aerodynamic Characterestics of a Body of Revolution at Mach Numbers from 0.25 to 1.90, NASA TN D-1300, 1962.

[19] Wang, C.Y. Contours for Stagnation Point Mass Injection in Hypersonic Flow, AIAA J., Vol.2, 1964.

[20] Casanova, R.A. and Wu Ying-Chu, L. Flow Field of a Sonic Jet Exhausting Contour to a Low Density Supersonic Airstream, Phys. Fluid, Vol. 12, 1962.

[21] Owen, P.R. and Thornhill, C.K. The Flow in a Axially Symmetric Supersonic Jet from a Nearly Sonic Orifice into a Vacuum, ARC R&M No. 2616, 1952.

[22] K.KARASHIMA and K.SATO. An Experimental Study of an opposing Jet, Report of Institute of Aeronautical laboratory, University of Tokyo, Vol. 11 No 1(A), 1975, pp.53-64. (In Japanese)