NUMERICAL SIMULATION AND PARAMETRIC STUDY OF HARTMANN-SPRENGER TUBE BASED POWERED DEVICE

A. Hamed*, K. Das** and D. Basu**

Department of Aerospace Engineering and Engineering Mechanics

University of Cincinnati

Cincinnati, Ohio-45221-0070

Abstract

Numerical simulations of unsteady flow in a Hartmann resonance tube are carried out with the goal of understanding the effect of jet Mach number on the flow characteristics. The device, which consists of a convergent nozzle facing a closed end tube produces a nearly normal shock that fluctuates in the gap between the nozzle and the tube. Numerical solutions were obtained for the unsteady Reynolds average Navier-Stokes equations using the WIND code. Computational results are presented for pressure fluctuations and sound pressure level (SPL) spectra at different jet Mach numbers. The results demonstrate different resonance tube operating modes depending on jet Mach number. The pressure fluctuations associated with each mode are similar to the experimentally measured pressure fluctuations in the jet screech and jet regurgitant modes.

Nomenclature

D=Exit nozzle diameter

L=Tube Length

S=Distance between nozzle and tube

M_j =Jet Mach number

X_s =Free jet shock distance from nozzle exit

Introduction

Hartmann¹ observed that high frequency pressure fluctuations are generated when an air jet oscillator such as a tube is placed facing an under-expanding jet from a nozzle. He reported that the high frequency pressure fluctuations are strongly dependent on the length of the tube and its distance from the nozzle. Hartmann explained that the tube should be placed in the compression region which he termed “zone of instability” in order to obtain high frequency tones. Sprenger² made an in-depth study of the effects of nozzle-tube spacing, nozzle stagnation pressure, and

tube length on the end-wall temperature. He observed large variations in end-wall temperature with slight changes in nozzle pressure ratio or spacing between nozzle and tube. The high temperatures and intense heating obtained at the resonance tube end wall due to high dissipation were studied by Rakowsky et al.³ for application as explosive igniter in rocket engines and scramjets.

Brocher et al.^{4,5} explained the flow oscillation mechanism in terms of compression and evacuation phases as the jet penetrates into the tube and compresses the air, then the compressed air is expunged out of the tube into the atmosphere. They carried out experiments for jet Mach numbers ranging between 0.1 and 2.0. A thin cylindrical body was placed at the nozzle center in order to achieve evacuation of the tube in the expansion phase. The measured pressure fluctuations’ frequency matched well those calculated from an analytical solution based on linear acoustic theory for $M_j < 1.0$ but were higher for $M_j > 1.0$. The oscillations’ amplitude was highest when the gap between the supply jet and the tube was equal to the tube diameter for subsonic jets and twice the diameter for supersonic jets.

Sarohia and Back⁶ identified three possible modes of operation from their experimental measurements of unsteady flows in a Hartmann tube, depending upon the tube, gap size, and jet Mach number. The first mode occurred only for the subsonic jets and was referred to as jet instability mode. In this mode a weak compression wave inside the tube was generated by the toroidal vortices that were created by the jet and grew in size as they moved downstream. In this mode the frequency of pressure fluctuations in the tube was equal to the vortex shedding frequency. The second mode of operation, which is widely discussed in literature, is the jet regurgitant mode. In this mode the pressure fluctuations are associated with the periodic swallowing and discharging of the jet flow at the tube fundamental resonance frequency. This mode was observed when the gap between the nozzle and the tube was greater than the free-jet shock location relative to the nozzle. The resonance tube switched

*Professor, AIAA Fellow

**Graduate Student, Student Member AIAA

from jet regurgitant mode to jet screech mode when the gap was equal to or less than the free-jet shock location relative to the nozzle. In this mode the normal shock in front of the tube inlet oscillated at a high frequency that was independent of the tube length.

Recently, Hartmann resonance tube based power devices have been used as high frequency actuators for suppressing noise in high speed jets and in open cavities^{7,8,9,10}. Raman et al^{11,12} developed a high bandwidth powered resonance tube actuator and though the variation of gap and tube length obtained the desired frequency. Kastner and Samimi¹³ used a planar flow visualization technique with a very short exposure time to obtain instantaneous and phase-averaged flow images for the exiting jet from a Hartmann tube. They studied the effect of tube length, jet Mach number, and separation distance on the power spectra of the far acoustic field and the near pressure field.

Hamed et al¹⁴ conducted a numerical investigation of the unsteady flow in a resonance tube in the jet regurgitant mode using the WIND code¹⁵. In that study a wake producing needle was placed on the axis of the convergent divergent nozzle as suggested by Brocher⁴ et al to ensure complete evacuation and filling of the tube. Results highlighted the characteristics of oscillations in the jet regurgitant mode, namely the high amplitude low frequency tones generated by the tube. The computed frequency from the power spectra of the pressure agreed with the analytical quarter wave relation based on linear acoustic theory.

The present numerical investigation of the unsteady Hartmann tube flow field focuses on the predictions of two different modes of operation at supersonic jet velocities. The simulations were carried out using the WIND code as in our previous investigation¹⁴. The configuration in the present simulations consisted of an under expanded jet from a convergent nozzle facing a constant area tube which is closed at the opposite end. The simulations were performed over a range of nozzle pressure ratios resulting in different jet Mach numbers. Computational results are presented for the unsteady flow and acoustic features of the resonance tube in the screech and jet regurgitant modes.

Geometry and Computational Domain

A schematic of the Hartmann resonance tube device for the present study is shown in Figure 1. The nozzle and tube geometry are similar to the ones tested by Kastner and Samimi¹³. The current simulations were conducted for axi-symmetric flows, while the gap was partially closed in some of the experimentally tested configurations¹³. The gap between the nozzle exit and the tube inlet was equal to D and the tube length to exit nozzle diameter ratio was equal to one. The computational domain which is shown in Figure 2 was 12 times the nozzle exit diameter, D , in the radial direction, and extended from the inlet duct to the closed end of the $L/D=1$ tube in the axial direction. The computational domain was decomposed into six blocks as shown in Figure 2. The number of grid points in each block are also shown in the Figure 2.

Methodology

The unsteady compressible viscous flow solutions were obtained for the compressible Navier-Stokes equations in conservation law form using the WIND code. Van-Leer second order scheme and Jacobi implicit operator with 30 sub-iterations in each time step were used with four-stage Runge-Kutta time stepping scheme. A TVD factor of 1.0 was used, to enable TVD flux limiter in the explicit operator to prevent overshoots in flowfield properties in regions of high gradients. The turbulence was simulated using a combination of Baldwin-Lomax and P.D. Thomas algebraic turbulence model in the boundary layer and shear layer regions respectively. Arbitrary inflow boundary conditions were applied at the nozzle inlet. Viscous no slip boundary conditions were used at the nozzle and tube surfaces. Extrapolation was applied at the free stream boundaries.

Results and Discussions

The free stream Mach number, static pressure and static temperature were set to 0.05, 14.96 psia and 519°R respectively. Results are presented for four different operating conditions (Table 1). The simulations were conducted for nozzle pressure ratios of 2.13, 2.30, 2.89 and 5.74. These operating conditions will be identified henceforth in terms of jet Mach number M_j that would be obtained in ideal full expansion. The values of M_j for the simulated nozzle pressure ratios are 1.1, 1.16, 1.33 and 1.6. The simulations were performed over 6 million time steps of 4.2345×10^{-8} seconds for each case. It took 0.5

million time steps to purge the transient flow and establish the tube resonance.

Numerical simulations were first carried out for the flow field without the tube. The computational results presented in Figure 3 show the initial jet expansion and subsequent formation of shocks in the free jets. The figure shows that the free shock strength and its distance from the nozzle exit increase with increased jet Mach number. Sarohia and Back⁶ deduced from their experimental observations that the placement of the tube inlet relative to free-jet shock determines whether the device operates in the jet regurgitant or screech mode (aft and fore). For the computed Hartmann resonance tube geometry the tube end wall would be at the RHS boundary of Fig 3. The indicated position in the figure imply that the tube inlet location relative to the free jet shock is aft for $M_j=1.1$ and 1.16 ahead of $M_j = 1.8$ and only slightly ahead of $M_j = 1.33$.

The computed instantaneous Mach number contours are presented in Fig 4 for $M_j=1.16$ and $M_j=1.6$. According to this figure a nearly normal shock is formed in the jet between the nozzle exit and the tube inlet. The shock location and strength changed with the operating condition, M_j . The computed mean value and standard deviation of the static pressure along the axis are shown in Figure 5 for all four cases. These figures indicate that the shock fluctuates over larger distance at the lower free jet Mach numbers and the pressure fluctuations behind the shock decays faster at the higher jet Mach numbers.

Figures 6 and 7 present the velocity vectors contours inside the tube at four different times during the resonance cycle. The velocity vectors in Figure 6 clearly illustrate the filling and evacuation phases at the lower jet Mach numbers of 1.1 and 1.16. On the other hand, the velocity vectors in Figure 7 do not indicate distinct tube filling or evacuation at the high Mach numbers of 1.33 and 1.8.

Typical pressure fluctuations and power spectra behind the shock and the tube end wall are presented in Figure 8 and 9. Tonal frequencies are observed in the power spectra at the lower jet Mach numbers. On the other hand, the SPL is seen to have a broadband content over a wide range of frequencies with no tonal frequencies at $M_j=1.8$. In addition, the figures indicate that the pressure oscillations amplitude increases with jet Mach number from 1.1 to 1.16. This is in agreement with the experimental observation of Sarohia and Back⁶ in the jet regurgitant mode. The first tonal frequency (4500 Hz) was found to be in agreement with the quarter

wave frequency for the resonance tube based on the linear acoustic theory. On the other hand, the pressure oscillations amplitude is much lower at the higher jet Mach numbers, ($M_j=1.33$ and 1.8). This is also in agreement with the observations of Sarohia and Back⁶ when the tube operates in the screech mode. Overall, the predicted mode switch in the computational results is consistent with the experimental observations of Sarohia and Back⁶.

Summary

The computed unsteady flow field in a powered Hartmann resonance tube is presented at four different operating conditions. The results illustrate a switch in the mode of operation with increasing jet Mach number consistent with experimental observations. At the lower jet Mach numbers the tube operates in jet regurgitant mode in which filling and evacuation of the tube produced distinct tones. In this mode the first SPL peak frequency agreed with the tube quarter wave frequency and the pressure fluctuations amplitude increased with increasing jet Mach number. Whereas, at the higher Mach numbers the tube operates in the jet screech mode in which the sound pressure level spectra has a broad band content over wide range of frequency and no predominant tones.

Acknowledgements

This research was supported by DAGSI grant, AFRL/VA-UC-00-01. The authors would like to thank Mr. Dennis Yoder of NASA GRC for his valuable suggestions regarding the WIND code, Prof. M. Samimy of Ohio State University for proving the nozzle geometry and Mr. Robert Ogden of UC for providing technical support. Some of the computations were performed on Origin-2000 at the Ohio supercomputer center.

References:

1. Hartmann, J., and Trolle, B., "A new Acoustic Generator," J. Sci. Instr., Vol. 4, pp. 101-111, 1927.
2. Sprenger, H.S., "Über Thermische Effekte bei Resonanzproblem," Mitteilungen aus dem Institut für Aerodynamik an der E.T.H., Zurich, Nr 21 18
3. Rakowsky, E.L., Corrado, A.P., Marchese, V.P., "Fluidic explosive ignitor", Fluidics Quarterly, Vol. 6, pp 13-32, 1974
4. Brocher, E., Maresca, C. and Bornay, M.H., "Fluid Dynamics of the resonance tube," J. of Fluid mech., Vol. 43, Part 2, pp.369-384, 1970.

5. Brocher, E., Maresca, C. Journal of Mechanics, Vol 8 pp21, 1969.
6. Sarohia V and Back, L.H. "Experimental investigation of Flow and Heating in a Resonance tube," J. of Fluid mech., Vol. 94, Part 4, pp.649-672, 1979.
7. Raman, G., Mills, A., Othman, S., and Kibens, V., "Development of Powered Resonance Tube Actuators for Active Flow Control," ASME FEDSM 2001-18273, June 2001.
8. Stanek, M. J., Raman, G., Kibens, V., Ross, J. A., Odedra, J., and Peto, J. W., "Control of Cavity Resonance Through Very High Frequency Forcing," AIAA Paper 2000-1905, June 2000.
9. Stanek, M. J., Raman, G., Kibens, V., Ross, J. A., Odedra, J., and Peto, J. W., "Suppression of Cavity Resonance Using High Frequency Forcing – The Characteristic Signature of Effective Devices," AIAA Paper 2001-2128, June 2000.
10. Raman, G., Kibens, V., Cain, A., and Lepicovsky, J., "Advanced Actuator Concepts for Active Aeroacoustic Control," AIAA Paper 2000-1930, June 2000.
11. Raman, G., Khanafseh, S., Cain, A.B., "Development of high bandwidth actuators for aeroacoustic control," AIAA Paper 2002-0664, January 2002.
12. Raman, G., Khanafseh, S., Cain, A.B., "High bandwidth powered resonance tube actuators with feedback control (for active flow control)," AIAA Paper 2002-2820, January 2002
13. Kastner, Jeff and Samimy Mo, "Development and Characterization of Hartmann Tube Base Fluidic Actuators for High Speed Flow Control," AIAA Paper 2002-0128, January 2001.
14. Hamed, A., Das, K., and Basu, D., "Numerical Simulation of Unsteady Flow in Resonance Tube," AIAA Paper 2002-1118, January 2002.

Table 1. Resonance Tube Operating Conditions

Jet Mach number	Nozzle Inlet Total Pressure (psi)	Nozzle Inlet Total Temperature ($^{\circ}$ rankine)	Nozzle Pressure Ratio
1.1	31.94	644.598	2.13
1.16	34.44	658.67	2.30
1.33	43.18	702.61	2.89
1.8	85.94	855.31	5.74

Figure. 1. Schematic of resonance tube

Figure 2. Solution Domain

$M_j = 1.1$

$M_j = 1.16$

$M_j = 1.33$

$M_j = 1.8$

Figure 3. Free-jet shock structure.

(a) $M_j = 1.1$

(b) $M_j = 1.8$

Figure 4 Mach number contours in Resonance tube

(a) $M_j=1.1$ (b) $M_j=1.16$ (c) $M_j=1.33$ (d) $M_j=1.8$

Figure 5. Mean and Standard Deviation of Static Pressure along the centerline

(a) $M_j=1.1$

(b) $M_j=1.16$

Figure 6. Velocity vectors inside tube

(a) $M_j=1.331$

(b) $M_j=1.8$

Figure 7. Velocity vectors inside tube

 $M_j=1.1$

 $M_j=1.16$

 $M_j=1.33$

 $M_j=1.8$

Figure 8. Pressure fluctuations and power spectra behind shock.

$M_j=1.1$

$M_j=1.16$

$M_j=1.33$

$M_j=1.8$

Figure 9. Pressure fluctuations and power spectra at tube end wall.