Experimental Investigation of Acoustic Characteristics of Compressible Vortex Ring

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Abstract

Sound generated during formation and propagation of a compressible vortex ring is studied experimentally using microphone measurements and pulsed laser based high speed flow visualization. Vortex rings are generated in the open end of a shock tube for shock Mach number 1.3 and for different driver section lengths. It has been observed that sound generated during the initial rollup of vortex sheet is dominant than the other processes of vortex ring propagation such as growth, secondary and tertiary ring formation, and pinching-off process. Wavelet transform based analysis identifies the generation of sound during these discrete events. High speed flow visualization pictures are used to verify the time of occurrence of these different discrete phenomena of vortex ring evolution. The angular distribution of the vortex ring's evolution sound shows that the maximum sound is produced in the region of 0 to 30° from the axis of the shock tube.

1. Introduction

In many practical fluid flow phenomenons, sharp changes in the velocities (vorticity) occur over a thin layer of fluid flow and at the other layers, the changes in velocities are negligible. There are two major classes of such flows exists namely the boundary layers flows where the shear layer is attached with the solid surfaces and free shear layers in the fluid. Free shear layers arise in many natural flows such as in the atmosphere and in the oceans, as well as in jets and the mixing of fluid streams in the industrial processes. Free shear layers have received special attention in recent years due to the wide spread interest in coherent structures in turbulent flows and the flow field of jets, atmospheric plumes and wakes behind any axisymmetric bodies. These coherent structures diffuse slowly in the irrotational fluid, and moves large distances due to their self induced motion and interaction. The dynamics of these flows involves complex phenomenon, such as formation and interaction of coherent vortices whose nature is not well understood.

Vortex rings are clean vortical structure of bounded volume of fluid with concentrated vorticity which is produced by giving small impulse in many different ways. There has been lot of literature for incompressible vortex ring formation (Glezer[1], Orlandi[2], Lim[3], Gharib *et al*[4], Mohseni, and Gharib[5]), interaction (Orlandi[6], Fabris and Liepmann[7], Chu *et al*[8]), and its instability (Hattori[9], Dazin *et al*[10]). The detailed review of incompressible vortex ring was given by Shariff and Leonard[11]. There are studies on compressible vortex ring's flow field analysis (Elder and Hass[12], Baird[13], Brouillette and Hébert[14], Mohseni[15], Sun and Takayama[16] and Arakeri *et al*[17]), interaction (Minota *et al*[18-20], Takayama *et al*[21], Kontis *et al*[22]), and their sound generation during interaction (Minota *et al*[23], Inoue, and Takahashi[25], Tang, and Ko[26]). Aerodynamic sound is basically a part of flow energy which is emitted during shear layer interaction. Sound produced from jets, and in more complex flows like combustion is due to unsteady interaction of vortices among themselves and with the shear layers.

Lighthill[28] found that the generation of sound in an ideal and stationary medium is predominantly by the fluctuating Reynolds stresses in the flow. Reynolds stresses occurs in the fluid flow owing to instability, which yield regular eddy patterns in low Reynolds number flows and irregular turbulent flows in high Reynolds numbers. According to the theory of aerodynamics, sound emitted from the turbulent flow in the irrotational flow field is characterized by a quadrupolar emission. If the flow velocity is less compare to the speed of sound then sound emitted by the turbulent flow is less efficient compare to the interaction of eddy and solid body sound[23]. The far field acoustics fluctuations in free space produced by vortices are linearly dependent on the flow vorticity in accordance with general theory of Obermeier[29]. Hence, the vorticity generated during the formation and propagation of vortex ring is responsible for far field acoustic fluctuation in the irrotational field. Sound from the shock tube generated compressible vortex ring is complex due to the presence of incident shock. The signal obtained from the transducer contains strong pressure rise due to incident shock followed by vortex ring formation and its propagation sound.

In the present study, sound generated during the formation and propagation of compressible vortex ring for shock Mach number 1.3 with variable length trailing jet is studied experimentally. The far field acoustic pressure generated by the evolution of a compressible vortex rings is measured using microphone at 2m location from the exit of the shock tube. The strong pressure rise due to the incident shock wave is filtered from the microphone signal by fitting an appropriate curve that represents the shock signature and subtracting it from the pressure signal. Strengths of the acoustic fluctuations for different phenomena such as formation of primary vortex ring at exit, secondary and tertiary rings at the surface of the trailing jet are obtained from this fluctuating pressure. The time of initiation of different process and its duration of formation are obtained from the fluctuating signal obtained after filtering the shock using discrete wavelet transform (DWT). High speed flow visualization pictures obtained using Pulsed laser and CCD camera are used to verify the results obtained from the wavelet analysis.

2. Experimental setup and apparatus

A cylindrical shock tube made of steel is used for generating the compressible vortex ring[27, 31]. It has a maximum driver section length of 300mm and the driven section length of 1200 mm with inner and outer diameter of 64 mm 100 mm respectively. The exit of the tube has 60° tapering to make a sharp opening. The entire phenomenon of compressible vortex ring evolution takes place in few milliseconds. Hence, the shock tube is kept at the height of 1.7m from the ground to avoid any ground reflection of shock during the measurement time. The microphone is kept at 2m from the exit of the tube; for an average shock speed of 441m/sec, the first reflected shock from the ground reaches the microphone not before 8.9ms (for 1m location 8ms). As the evolution process of the vortex ring of interest is for first 5ms, this height is enough for positioning the shock tube. ¼ inch B&K (No 4939) microphone is used for acoustic measurements. The data acquisition is done with the sampling rate of 100KS/s using NI 4472 24 bit sound and vibration DAQ card. The shock tube stand angles are covered using foam to avoid any significant reflection of shock from them. All experiments are performed with the helium as a driver section gas. Mylar sheets of different thicknesses are used as diaphragm which is ruptured using a heated nichrome wire. The shock speed is measured from the flight time of shock between two stations using two pressure transducers which are kept at 300mm apart inside the shock tube. Similarly the shock velocity at different stations outside the shock tube is measured using two hotwires placed at a known short distance between them. For flow visualization, a pulsed laser along with a CCD camera is used to capture the flow field of compressible vortex ring. The laser is triggered and synchronized with the camera using external trigger unit which gets the triggering signal from the second pressure transducer. Two consecutive images are taken with the time difference of 40µs using double shutter mode in CCD camera to get the propagation velocity of the vortex ring. In all microphone and flow visualization pictures t=0 represents the shock at the exit.

3. Results and discussion

The most of the physical signals are unsteady in nature which has non stationary signal. Wavelet analysis is a tool to find not only the frequency but also the time at which the events of those frequencies occur. One major advantage afforded by wavelets is the ability to perform local analysis. A wavelet is a waveform of effectively limited duration that has an average value of zero which tends to be irregular and asymmetric. Wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet. The wavelet transform of the fluctuating pressure signal reveals aspects like trends, breakdown points, discontinuities in higher derivatives, and self-similarities in the signal. The Discrete Wavelet Transform (DWT) split the entire range of frequencies into low and high frequencies parts. The low frequency part contains the frequency up to $F_{max}/2$ and the high frequency part contains the frequency from $F_{max}/2$ to F_{max}. This is used to find the low frequency and high frequency parts exist in the signal. The formation of vortices is a rapid process which has high frequency contents and it is found from the DWT analysis along with the shock.

Fig. 1a shows fluctuating pressure signal obtained from microphone which is kept at 30° and 2m location from the exit for driver section lengths 115mm. Here the time of arrival of shock at the microphone is referred as t=0. Pressure rise due to the incident shock presence in the microphone signal is fitted with appropriate curve (Exponential or Gaussian fit). This fitted curve is removed from the microphone signal to obtain the fluctuating pressure signal during the formation and propagation of primary vortex ring (Fig. 1b). It is observed form Fig. 1b that the acoustic pressure rise during the initial rollup of shear layer is dominant than the other sound. The fluctuations followed by this sound are due to the growth of the primary vortex ring, formation of trailing jet vortices and pinching-off. The high fluctuating pressures at t~1ms in Fig. 1b are due to initiation of pinching-off process and formation and growth of secondary vortices. These events are identified from the discrete wavelet analysis of the fluctuating signal. Fig. 1c & Fig. 1d shows the low frequency and high frequency components of fluctuating signal obtained using second order Debauches family mother wavelet. The high frequency components shows few discrete high frequencies zones. The discrete high frequency events at t~0.02ms (Fig 1d) are due to initial rollup of vortex ring. The vorticity production is high during this initial rollup. The discrete frequency events up to 0.5ms are due to growth of the primary vortex ring. Discrete events at time 0.9ms and 1.2ms are due to the formation and the growth of secondary and tertiary vortices at the surface of trailing jet and initiation of pinching-off process. Hence the driver section length is small, the primary vortex ring detaches from the trailing jet at around 1020µs. Discrete frequencies at 1.8ms are due to growth of the secondary and subsequent vortices during this time primary vortex ring already detached from the trailing jet. The flow visualization pictures in Fig. 1e are used to verify these phenomena. The secondary and tertiary vortices formed at the trailing jet are not strong (Compared to next cases) which are seen in Fig. 1b and Fig. 3b. This is due to sudden reduction of trailing jet velocity due to short driver section (115mm). Hence the vorticity production and sound generation during these processes are less.

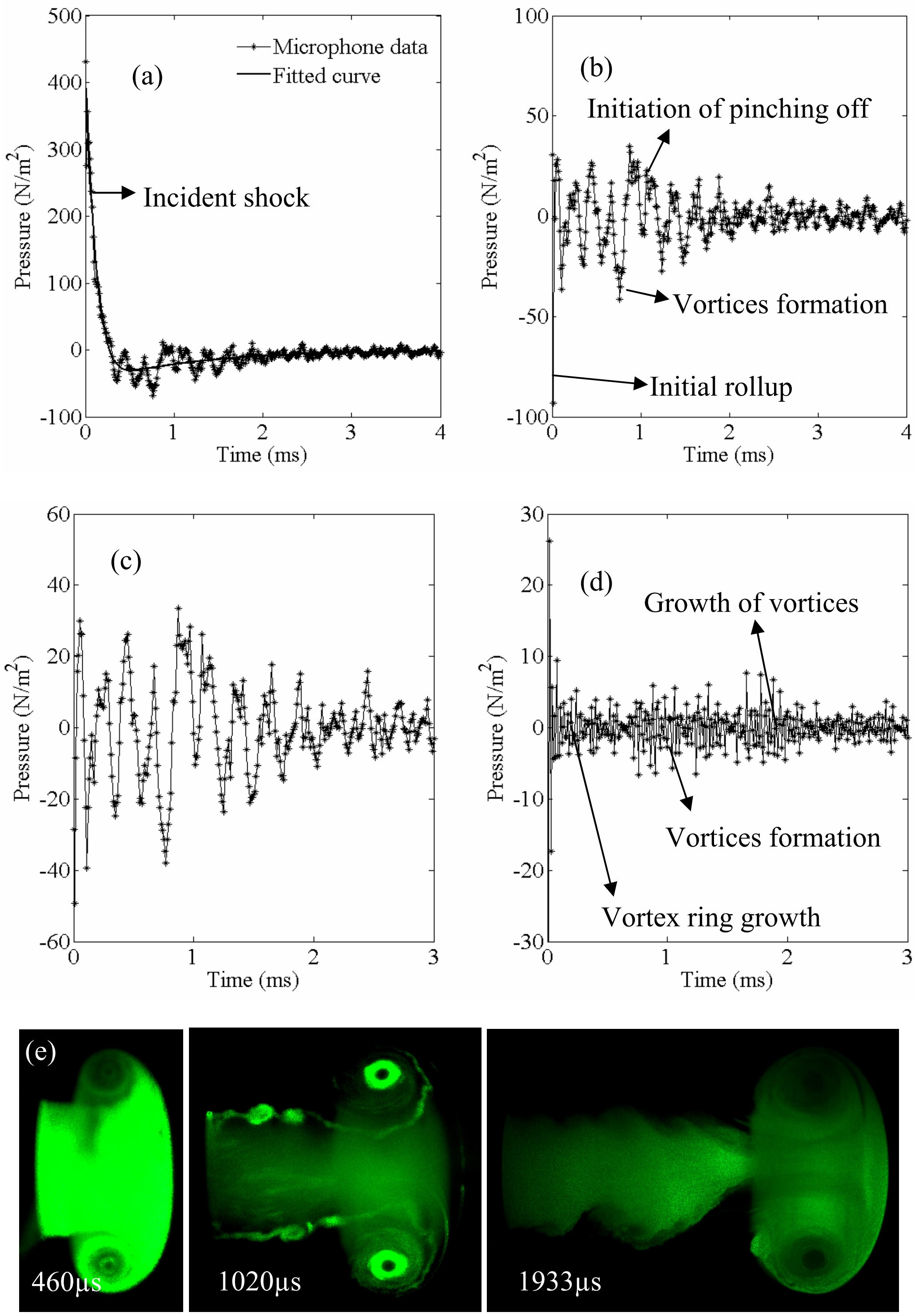

Fig. 1 (a) Microphone signal with fitted curve (b) Fluctuating pressure signal (c) Low frequency components & (d) High frequency contents of the fluctuating pressure signal (e) Flow visualization pictures for shock Mach number 1.3 with driver section length of 115mm

Fig. 2 shows the acoustic pressure signal and the corresponding flow visualization pictures for shock Mach number 1.3 with the driver section length of 150mm. Strong pressure rise at t~0ms in Fig. 2b and Fig. 2d shows the initial rollup of primary vortex ring. In Fig. 2b, the strong pressure rise at around 1ms is due to strong vortex formation at the surface of the trailing jet. Flow visualization at time t= 1120μs shows the rolling process of this trailing jet vortex and initiation of pinching-off process. Flow visualization picture at t=1933μs shows the free travelling stage of primary vortex ring. The discrete acoustic pressure rises seen in Fig. 2d at time around 2ms are due to the growth of the trailing jet vortices.

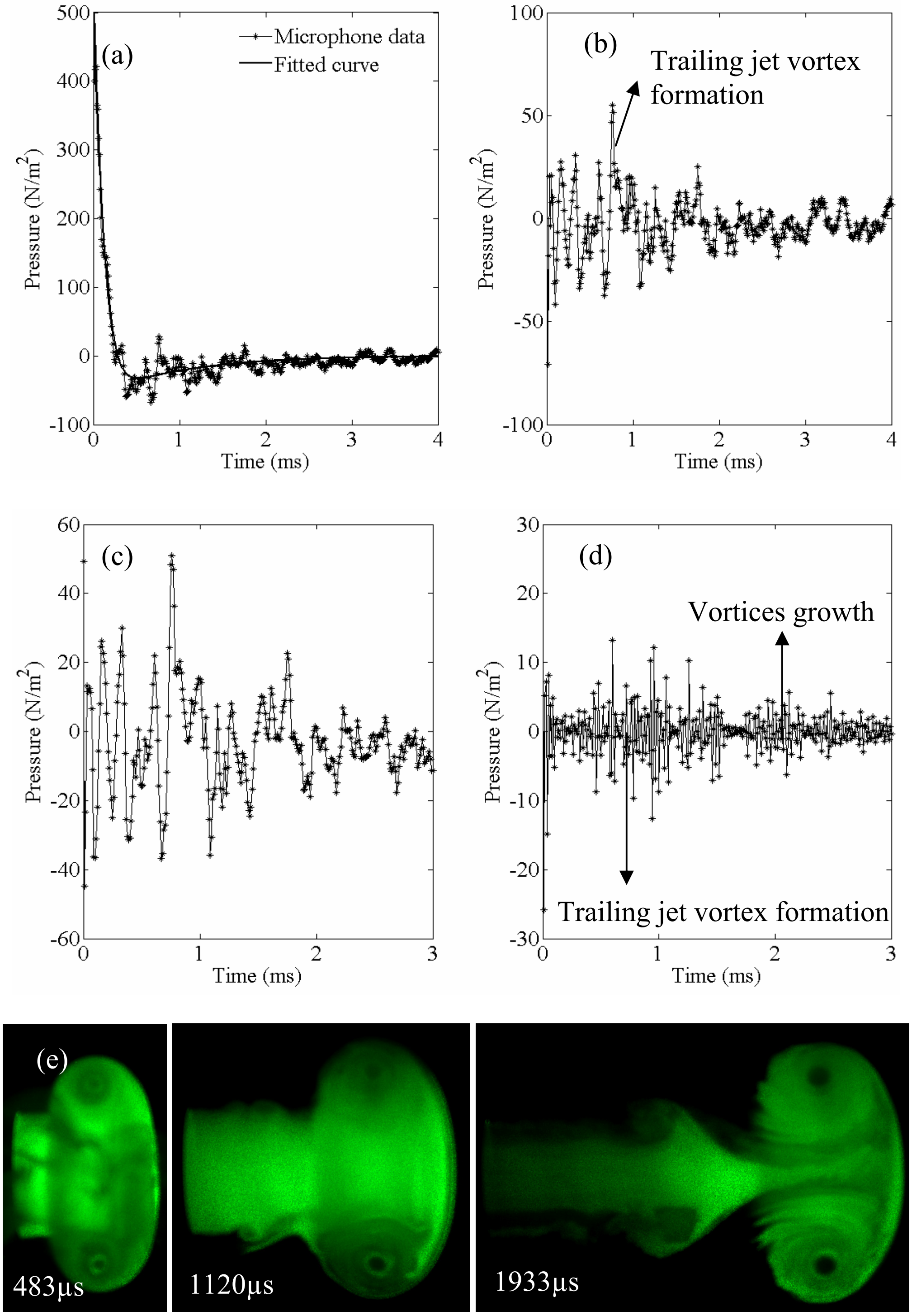

Fig. 2 (a) Microphone signal with fitted curve (b) Fluctuating pressure signal (c) Low frequency components & (d) High frequency contents of the fluctuating pressure signal (e) Flow visualization pictures for shock Mach number 1.3 with driver section length of 150mm

Fig. 3 shows the acoustic pressure signal and the corresponding flow visualization pictures for shock Mach number 1.3 with the driver section length of 300mm. The strength of the incident shock (compare Fig. 1a & Fig. 3a) for long driver section is high due to higher velocity behind the shock whereas for smaller driver section the expansion waves catches up the incident shock and reduces its strength. The length of the trailing jet is more for this longer driver section case which causes the vortex ring to attach with the trailing for longer duration which is seen in Fig. 3e at time 1013µs.

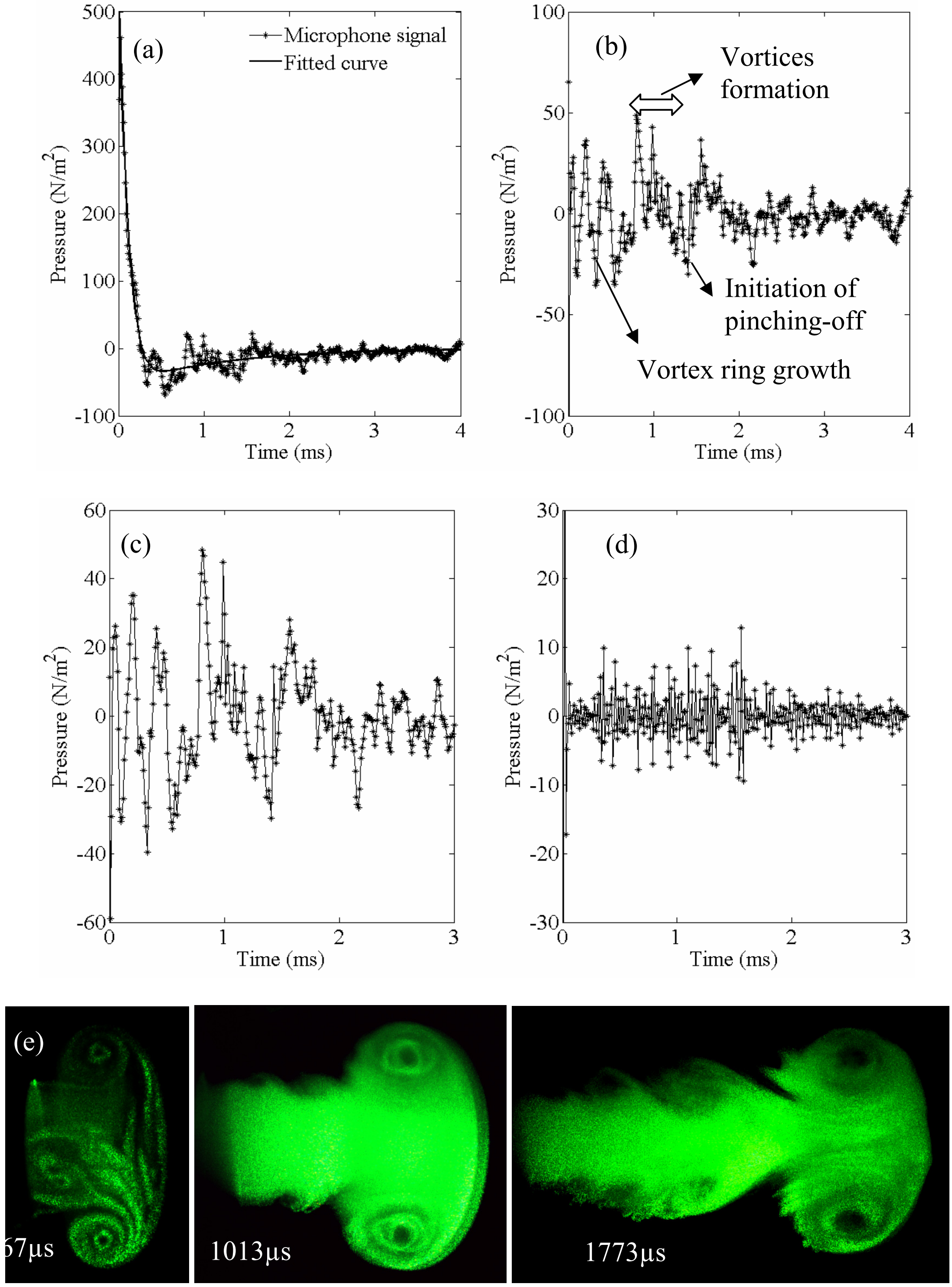

Fig. 3 (a) Microphone signal with fitted curve (b) Fluctuating pressure signal (c) Low frequency components & (d) High frequency contents of the fluctuating pressure signal (e) Flow visualization pictures for shock Mach number 1.3 with driver section length of 300mm

Fig. 3b shows fluctuating pressure signal obtained after filtering the incident shock. There are many strong acoustic pressure rises in this signal compare to the smaller driver section length (115mm). The strong pressure rise at t=0ms is due to initial rollup of primary vortex ring. The sharp pressure rises followed this are due to the growth of the primary vortex ring and its translation along the trailing jet. Hence the velocity at the exit is higher which causes more vorticity production during the growth of the vortex ring. The strong acoustic pressure rises seen after 0.5ms are due to propagation of vortex ring along with the trailing jet and initiation of formation of sequences of secondary vortices at the surface of the trailing jet. Fig. 3d shows the time of occurrence of these trailing jet vortices formations and its growth. These vortices are much stronger than the vortices generated for smaller driver section (115mm). Flow visualization pictures at time t=1013µs and t=1773µs show the propagation of vortex ring with trailing jet and the continuous formation of trailing jet vortices at the surface of the trailing jet.

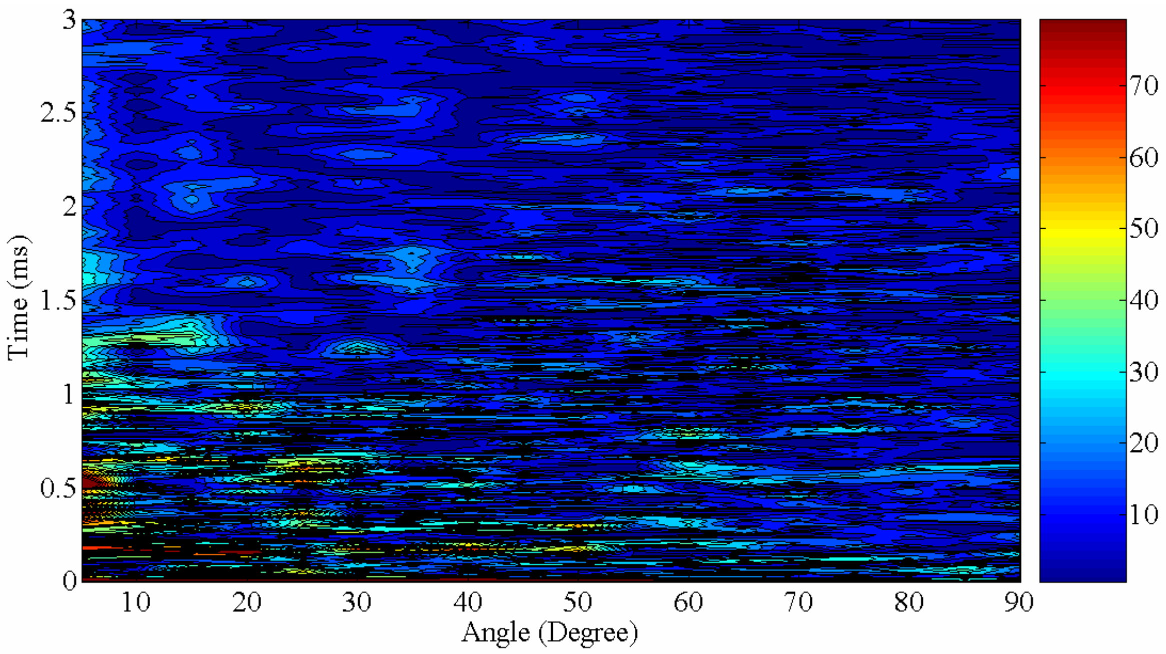

Fig. 4 Radial distribution of sound strength for shock Mach number 1.3

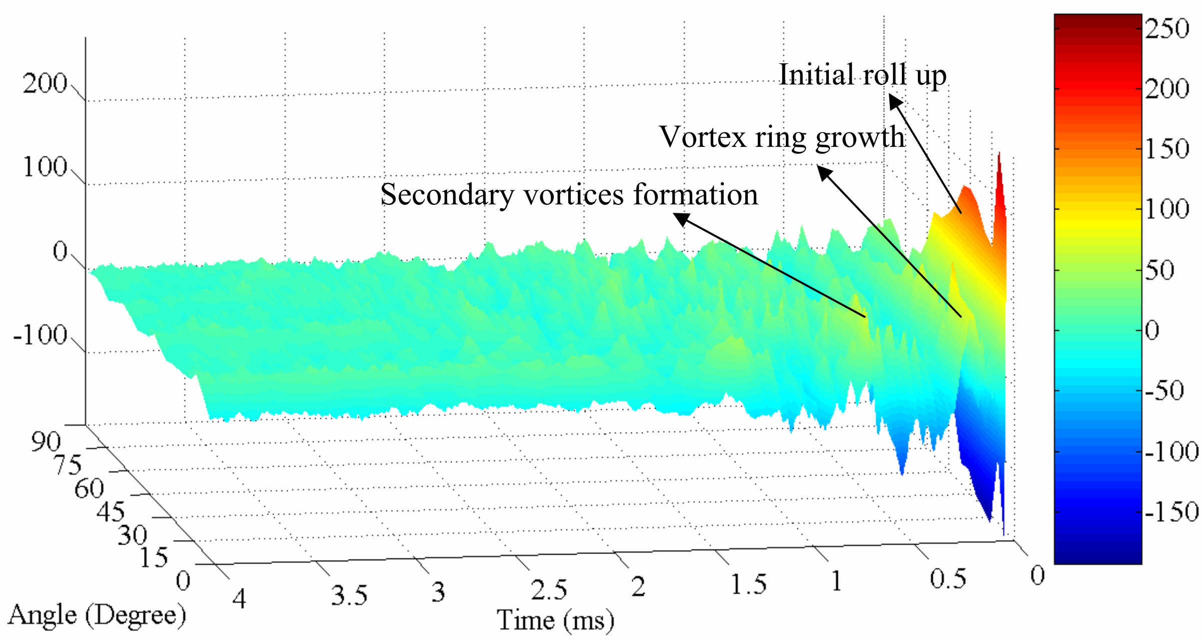

Fig. 5 Surface plot of radial distribution of sound at 2m for shock Mach number 1.3

Fig. 4 and Fig. 5, the contour and surface plots show the radial distribution of fluctuating pressure signal obtained after removing the incident shock from the microphone signal for shock Mach number 1.3 with the driver section of 300mm at 2m distance from the exit of the tube where angle 0 is along the axis of the vortex ring. It is observed from Fig. 4 that the acoustic fluctuation generated during the formation and propagation of vortex ring is more towards the axis of the vortex ring propagation and the initial rollup sound is more. The strength of the sound generated during the evolution of vortex is small along the perpendicular direction of the propagation of vortex ring. The surface plot Fig. 5 shows the strength of the acoustic fluctuation along the radial direction where the sound generated after 1.5ms is very slow. This is due to slow decay (less vorticity production) of primary vortex ring. After the pinching-off, this ring move long distance before it collapses into a turbulent structure. It is observed from Fig. 5 that sound generated during the initial rollup of vortex ring after the diffraction of shock at the exit is dominant than the other noise sources such as the growth, formation of secondary and tertiary vortices, pinching-off, and the decay of vortex ring vorticity during the course of motion.

4. Concluding remarks

Sound generated during the formation and evolutions of vortex ring for shock Mach number 1.3 and different driver section lengths are studied. Sound generated during the occurrences of different phenomenon such as initial rollup of shear layer at the exit, growth of vortex ring, formation and growth of secondary and tertiary vortices and pinching-off are identified and verified with the sequence of flow visualization pictures. If the driver section length is small (115mm) then the vortex ring pinches-off from the trailing jet early and the vortices generated at the trailing jet are weak and produce less acoustics fluctuations. This shows the propagation clean vortex ring. Whereas, for longer driver section (300mm), the primary vortex ring travels with trailing for some time before it pinches-off from the trailing jet. The vortices formed at the surface of the trailing jet are strong compare to the small driver section cases and produces strong acoustic pressure rise. Sound produced during the initial rollup of vortex ring formation after the diffraction of incident shock at the exit is more than the other processes of vortex ring evolution in all radial directions. Sound produced is more towards the axis of the vortex ring from 0° to 30° and weak in the direction perpendicular to the axis of vortex ring.

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