Experimental Thermal and Fluid Science 79 (2016) 85–90

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Three-dimensional shock wave distortion in shock-square vortex loop interaction

Takahiro Ukai [a],*, Hossein Zare-Behtash [a], Konstantinos Kontis [a], Shigeru Obayashi [b]

[a] School of Engineering, University of Glasgow, Scotland G12 8QQ, UK
[b] Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan

ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 23 June 2016
Accepted 26 June 2016
Available online 27 June 2016

Keywords:
Shock wave interaction
Square vortex loop
Shock wave focusing

ABSTRACT

Understanding of the three-dimensional shock wave-vortex loop interaction phenomena plays a key role in noise reduction. This study focuses on the three-dimensional shock wave distortion and propagation phenomena in a near-field supersonic jet. Shock-square vortex loop interaction was experimentally investigated in a square cross-sectional open-end shock wave generating tube at an incident shock Mach number of 1.39 ± 0.05. A square vortex loop impinged on a reflected shock wave from a wall located in front of the nozzle end. The planar reflected shock wave transforms into either a concave or convex distorted shape due to the opposing high-speed flow emitted from the nozzle corner. The convex shaped shock wave scatters towards the outside of the vortex loop, whereas the concave one converges towards the centre of the vortex loop. The concave shaped shock wave results in shock wave focusing. In shock-square vortex loop interaction, the shock wave is locally focused along the axis of the nozzle corner.

1. Introduction

Compressible vortex loops are mainly generated by shock wave emission through a tube into a quiescent fluid. Their flow features are strongly related to the nozzle geometry of the tube. After an incident shock wave is emitted from the nozzle exit, the shock wave diffraction generated at the nozzle corner induces an initial circulation which develops into a vortex. The angle of the nozzle corner is an important factor in vortex circulation [1–3]. Sun and Takayama [3] numerically conducted vorticity prediction in shock diffraction at various corner angles and showed that the vorticity production dramatically increases in the range of 15–45 degrees; however, it hardly increases at corner angles over 90 degrees and reaches a constant value. When three-dimensional fluid motion is taken into account, shock wave diffraction leads to the generation of a vortex loop. Circular vortex loops that produce fundamental three-dimensional fluid motion are frequently addressed in vortex loops studies [4–7]. The main features of vortex loops are that they are self-contained, automotive, and quite longevous [8]. Different exit nozzle geometries, which are non-circular in shape, change the flow characteristics and induce unsteady and highly three-dimensional flows. Zare-Behtash et al. [9,10] reported the flow features of non-circular vortex loops from various nozzle geometries such as the square, elliptic, and exotic shapes. The PIV results of Zare-Behtash et al. [10] indicated that the circulation of a circular vortex loop is higher than that of a non-circular one because the deceleration of some parts of the non-circular vortex loop induce a relatively lower circulation. According to the numerical simulation of Zhang et al. [11], a square vortex loop leads to counter-rotating stream-wise vortices at the four corners, and they accelerate mixing in the vortex core because they engulf the surrounding air into the vortex core. Therefore, the nozzle geometry is a key parameter influencing flow characteristics such as velocity and vorticity of a vortex loop, and various nozzle shapes are used for various engineering applications.

Rectangular supersonic jets have the ability to enhance mixing, reduce jet noise, and be applied for the thrust vector control [12]. Additionally, rectangular supersonic jets are useful for a wide range of applications such as combustion, noise suppression, heat transfer, and lift augmentation. According to previous investigations, where various nozzle geometries have been evaluated for jet noise reduction in high-subsonic and supersonic flows [13], a circular nozzle produces a higher level of jet noise, whereas a rectangular nozzle has a higher performance for noise reduction. Additionally, rectangular jets that play a key role in noise generation and jet plume impingement govern the performance of the vectored thrust on aircrafts. Screech tones, relating to jet noise generation, may also have a detrimental effect on aircraft structures. Raman [14] showed that the level of screech tones altered depending on a span-wise nozzle exit geometry. Rectangular jets have also been used for combustors [15,16] and they lead to enhancement of

---

* Corresponding author.
E-mail address: Takahiro.Ukai@glasgow.ac.uk (T. Ukai).

http://dx.doi.org/10.1016/j.expthermflusci.2016.06.028

the combustion performance due to axis switching associated with self-induced vortex ring deformations.

Shock waves generated in supersonic jets are often accompanied by induced vortex rings [17–19], and there is a high possibility that these flows interact with each other, which results in noise generation. Understanding shock-vortex loop interaction phenomena are important for noise detection/reduction in high speed flows [20–22] and the automobile exhaust flow fields [23–25]. Since the early 1990s, there have been experimental, numerical, and theoretical investigations of shock wave interaction with vortex rings [20–22,26,27]. Minota [28] experimentally investigated shock-vortex ring interactions when the shock wave impinges head-on. She showed that the diffracted shock wave which interacts with the vortex ring propagates towards the centre of the vortex ring, which results in the shock wave focusing at the centre of the vortex ring. This shock focusing causes a pressure increase that would lead to noise generation [29,30]. According to a numerical investigation by Meadows [31], the sound pressure level increases with increasing shock wave strength, and this relation was consistent with previous experimental observations in supersonic jets.

Understanding of shock wave interaction with three-dimensional vortex loop is also a key issue for noise generation. Shimizu et al. [22] experimentally and theoretically investigated the mechanism of noise generation in shock-vortex ring interaction in a three-dimensional flow field. They focused on investigating noise generation at the early stage of the interaction. Noise generation comes from the scattered waves involving the shock diffraction, the acoustic wave, and the backward scattering by density inhomogeneity. Inoue and Takahashi [32] numerically investigated sound generation in a long interaction process and showed large sound pressures occur due to shock wave focusing. Shock wave focusing in shock-vortex ring interaction had also been observed computationally by Takayama et al. [29]. Therefore, shock wave deformations such as diffraction, reflection, and focusing may lead to enhanced noise generation. Since non-circler vortex loops have self-induced vortex deformation, it leads to a more complicated mechanism for sound generation. This study focuses on investigating three-dimensional shock wave distortion and propagation phenomena. An experimental investigation of shock-square vortex loop interaction was conducted at an incident shock Mach number of 1.39 in a square cross-sectional open-end shock wave generating tube. The high-speed shadowgraph photography technique was used to evaluate flow characteristics.

2. Experimental setup

An experimental investigation was conducted in a square cross-sectional open-end shock wave generating tube at an incident shock Mach number of 1.39 ± 0.05 in the driven section with a Reynolds number of 7.2×10^5 based on a side length of the tube. The shock wave generating tube with side lengths of $d = 22$ mm consists of a driven section of 200 mm in length and a blasted section (Fig. 1). The wall thickness of the tube is 1.2 mm. A flush-mounted pressure transducer (Kulite Semiconductor Products, Inc., model: XTE-190M, natural frequency: 150 kHz) was positioned 50 mm from the exit of the tube, and the Mach number in the driven section is estimated from the measured overpressure magnitude. The pressure signal was recorded using a data acquisition (National Instruments Corp., model: NI-9205, sampling rate: 250 kS/s, resolution: 16 bit) driven by LabVIEW. A non-electric tube (Dyno Nobel, model: NONEL DynoLine) was used to induce a shock wave which propagates into the driven section. The shock wave generating system using the NONEL tube has been successfully applied in a previous study [33]. The flexible NONEL tube with an outer diameter of 3 mm was flush mounted on the shock generating tube end in the blasted section, and the axis of the NONEL tube was aligned with the shock propagation direction. The detonation was initiated within the NONEL tube by an electric blasting device (Dyno Nobel, model: Dyno Start 2, output voltage: 2500 V). This explosion generates a blast wave from the NONEL tube end, and the blast wave transforms into a planar shock wave in the driven section. NONEL tube of 300 mm in length was used for each run.

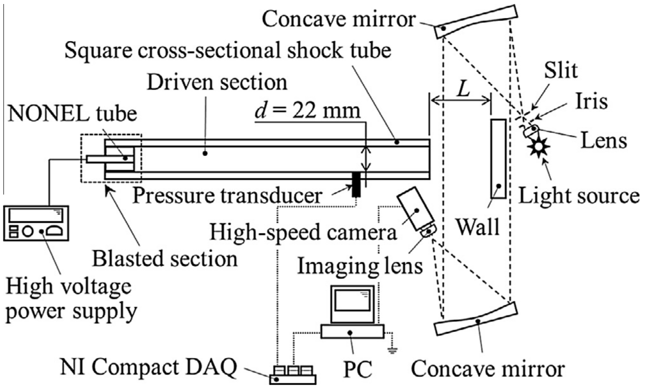

Fig. 1. Schematic of the experimental setup.

After the planar incident shock is emitted from the nozzle exit, a vortex loop is generated behind it, and its shape transforms with time (Fig. 2). The incident shock wave is reflected from a wall located in front of the nozzle exit, and this reflected shock wave impinges on the vortex loop. The distance between the wall and the shock generating tube was $L = 55$ mm. The velocity of the reflected shock wave just before vortex impingement was 317.6 ± 18.9 m/s which is a Mach number of less than 1.0. Shock-induced opposing flow might cause the reduction in the shock wave propagation speed.

High-speed shadowgraph photography with a standard Z-type optical arrangement was employed to visualise the flow density field. The shadowgraph system consists of a 450–1000 W continuous light source with an Xe-Hg arc lamp (Newport, model: 66921), a pair of 203.3 mm diameter concave mirrors with a focal length of 1829 mm, and a high-speed camera (Photron, model: Fastcam SA1.1). The images were acquired at a frame rate of 72 kfps with an exposure time of 1.0 μs. The offset angle between the collimated light beam and the light source was set to 19 degrees to prevent coma.

3. Results and discussion

Shadowgraph photography captures self-induced unsteady vortex motion, which enables us to understand the three-dimensional flow characteristics. Fig. 3 shows the time evolution shadowgraph images of the three-dimensional vortex loop without shock inter-

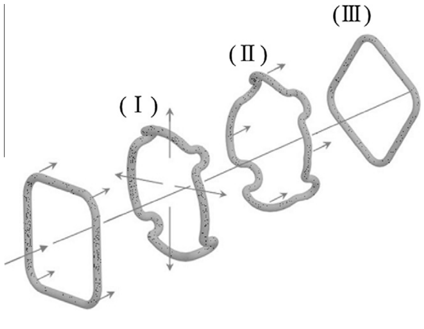

Fig. 2. Time sequential motion of the square vortex loop [10].