Evolution of the Transient Mach Disk

Brodie J. Norfolk *
Laboratory for Turbulence Research in Aerospace and Combustion, Monash University, Australia

Here we present a shock structure tracking technique and detailed discussion on the fluid dynamics of transient supersonic jets. We explore the fundamental fluid dynamics of transient supersonic jets with variation of the exit flow nozzle geometry and plate impingement. Our nozzle geometries include a convergent, divergent, and convergent-divergent design. The impingement of transient supersonic jets has previously been studied, however it is absent of extensive data, high quality schlieren, and variable exit geometry. We aim to address absences in the literature, explore in detail the shock-vortex interaction during jet impingement, and track the progression of the shock structure with a novel algorithm. Our discussion of the fundamental fluid dynamics governing the transient supersonic jet process details the affects of alternating the incident Mach number for, nozzle geometry variation on the shock-vortex interaction and jet plate impingement.

Nomenclature

M_1 = ambient Mach number

P_1 = ambient pressure, Pa

P_4 = shock tube driver section pressure, Pa

U_1 = ambient air velocity, m/s

U_4 = shock tube driver section air velocity, m/s

γ_1 = ambient specific heat ratio

γ_4 = ambient specific heat ratio

Subscripts

I. Introduction

Gas turbine engines are an integral component for the function of ground based power generation and aircraft engines. They account for a large percentage of power generation world wide. Thermodynamic cycle advances in gas turbine design play an important role in preventing the growth of emissions pollution and prolonged global warming

*Student, Department of Mechanical, Aerospace, and Mechatronics Engineering, Building 31, Monash University, Victoria 3800 , and AIAA Student Member.

[1]. Pressure gain combustion (PGC) is one possible to method of efficiency improvement. PGC is a constant volume combustion process that operates by increasing the stagnation pressure entering the turbine via heat released from combustion. Increasing the turbine inlet pressure allows for considerably more work to be extracted when the turbine expands the flow back to the free stream pressure. PGC optimises gas turbine thermodynamic cycle efficiency, and has the potential to increase current engine efficiency up to 10% [2].

PGC is at peak efficiency when accomplished through detonation driven combustion, this involves the implementation of detonation waves within the combuster to cause an increase in the temperature and pressure of the fuel-air mixture [3]. During combustion, detonation waves produce flow at supersonic velocities leading to an approximate constant volume and significant pressure gain across the combustor. For supersonic velocities high pressure turbine inlet flow must be steady. A possible method to achieve steady flow at the turbine inlet is via the implementation of a pulse detonation engine [4] with an equalising plenum chamber. Wear on the first stage of the turbine presents itself as one of the most significant problems of PGC implemetation in current engines. Replacing the combustor in a conventional gas turbine with a pulse detonation combustor (PDC) will result in the propergating detonation waves to converge on the first stage of the turbine. This overtime can lead to concentrated wear on the first stage of the turbine high wear stress points [5]. To alleviate turbine wear, the utilization of a high pressure plenum chamber is placed at the exit of the PDC, and creates steady flow conditions effectively shielding the first stage of the turbine from combustion detonations. It remains unclear on how to integrate a pressure plenum into a PDC design.

The fluid dynamics characterising the governing flow at the exit of PDC is defined as a shock-driven, transient, supersonic jet process [6]. The governing flow can be classified into several different stages [7] as shown in Figure **??**. The first stage of jet evolution is defined by the diffraction of a shock wave around the corners of the tube exit, this region is bounded by the curved part of the incident shock, the nozzle lip, and a reflected sound wave. In the next stage of jet evolution, a vortex ring is generated by the roll-up of the shear layer due to Kelvin-Helmholtz type instabilities along the slipstream at the nozzle lip [8, 9]. Kelvin-Helmholtz instabilities exist within the shock as a result of external perturbations (inhomogeneities in the flow) producing oscillations in the vortex sheet separating fluids with different flow characteristics. This structure propagates down the jet axis, and is simultaneously accompanied by the translation of a curved barrel shock formed initially at the nozzle lip. This instigates the formation of a curved Mach disk for a ratio of the nozzle exit to free-stream pressure exceeding 2.06 [10]. MORE ON MACH DISK

A triple point occurs between the leading edge of the barrel shock, the second shock, and the Mach disk. Given a sufficiently strong jet, a slip surface is generated downstream of the triple point. The first shock cell is formed in the third stage of jet evolution which is marked by the pinch-off phenomenon of the vortex ring, and signals the start of the trailing jet phase [11]. Separation of the vortex ring from the flow structure is driven by Kelvin-Helmholtz instabilities within the shear layer of the trailing jet [12]. The final stage of the supersonic jet is defined by the point at which the transient jet and vortex are no longer joined and the trailing jet forms. This is accompanied by the formation of a quasi-steady shock cell in self-sustained oscillation, radiating strong pressure waves.

Investigation into the high pressure plenum chamber required for PDEs currently has not been undertaken. However, the flow dynamics is considered analogous to the impingement of a transient supersonic jet on a flat plate. The governing dynamics of transient jet impingment can be classified into serveral stages as The physical process is initially characterised by the reflection of the incident shock wave on the impinging plate. The reflected shock wave propargates back towards the nozzle and interacts with the approaching vortex ring. The central section of the reflected shock wave is captured by the embedded rearward-facing shock at the centre of the vortex ring, and is intensified by the opposing high-speed flow. Simultaneously, the outer section of the shock wave is diffracted by the vortex core. This process results in the formation of a toroidal shock wave which focuses in the trailing jet along the longitudinal axis of flow. The next stage of the fluid dynamics is defined by the impingement of the propagating vortex ring. Initially, as the vortex ring approaches the wall, its propagation velocity decreases and its diameter increases due to the adverse pressure gradient present [13]. After votex impingement the vortical flow undergoes rapid radial expansion developing a boundary layer on the surface, which slows down the flow and increases the pressure distribution over the plate. After a given duration that is dependent on the initial incident Mach number, the boundary layer separates from the plate and the flow rolls up generating a series of secondary vortices. This also occurs at the thin shear layer present between the jet flow and the exterior fluid as the region rolls up due to Kelvin-Helmholtz instabilities. This produces small interacting secondary vortex rings that propagate towards the plate [14]. Cumulative interactions between the primary and secondary wall vortex rings result in a near standing lift off of the pair. The secondary ring subsequently merges with the primary ring, and the weakened newly formed vortex ring continues to translate down the plate.

II. Experimental Methods

A. Shock Tube Facility

The experiments presented were conducted in the LTRAC Supersonic Jet Facility. A schematic of the facility is shown in Figure **??**.

The facility utilises compressed air delivered by the Monash University compressed air supply system. To produce a canonical transient supersonic jet a shock tube model is adopted [15]. A typical shock tube consists of a high pressure section (driver section) and a low pressure section (driven section) separated by a diaphragm. Air enters the driver section until a desired pressure is reached, the diaphragm is then ruptured via a puncture from an actuated pin. Following the rupture, compression waves are fired down the driven section by the high pressure gas in the driver. As these compression waves travel down the tube they coalesce and form a shock wave that propagates into the test section, diffracts, and produces a transient supersonic jet. The shock tube model is fitted with a converging nozzle and impinging plate, shown in Figure **??**.

To prevent reflecting flow and acoustic feedback loop interference, the converging nozzle was designed with a 60° exterior angle and a 0.5*mm* lip. During the evolution of a transient supersonic jet, the vortex is fully formed at approximately 3 inner diameters from the exit for a conventional, no nozzle, shock tube [16]. As a result, an impingement plate distance is chosen DISTANCE AND WHY. The plate diameter is designed to appear infinite to the flow.

ENTER SHOCK TUBE FIGURE AND NOZZLE/PLATE FIGURE ENTER TABLE WITH DIMENSIONS

The relationship between the driver (4) pressure ratio and the ambient (1) pressure of the system is shown in Equation 1, and was utilised to calculate the design incident Mach number propagating from the shock tube [17].

$$\frac{P_4}{P_1} = \frac{2\gamma_1 M_1^2 - (\gamma_1 - 1)}{\gamma_1 + 1} \left(1 - \frac{\gamma_{4-1}}{\gamma_{1+1}} \frac{U_1}{U_4} \left(M_1 - \frac{1}{M_1}\right)\right)^{-2\gamma_4/\gamma_{4-1}} \tag{1}$$

B. Schlieren Imaging

The shock-driven, transient, supersonic jet is measured using a Toepler Z-type schlieren apparatus [18] (illustrated in Figure **??**) with the Shimadzu HPV-1 camera. The Shimadzu has a resolution of 312 x 260 pixels and a frame rate of up to 1 million fps.

ENTER SCHLIEREN SKEMATIC

C. Post Processing

Schlieren imaging produces a path integrated density gradient image that is excellent for flow visualisation but, is difficult to quantitatively extract physical parameters directly from image data. the required second order image derivatives are computed by convolution with the second order derivatives of the Gaussian kernel (reference). Mathematically this means that if f denotes the image and G the normalised Gaussian, we compute EQUATIONS where * denotes spatial convolution, x=(x,y) denotes the pixel position, and the derivative directions i and j can be x or y. The eigenvectors and eigenvalues are computed in the algorithm from a standard second derivative Hessian matrix

HESSIAN MATRIX Use a normalised ranking to threshold intensity lower then the 90th percentile

III. Results and Discussion

A. Converging Nozzle

B. Impinging Plate

C. Mach Number Variation

D. Convergence Study

IV. Conclusion

Although a conclusion may review the main points of the paper, it must not replicate the abstract. A conclusion might elaborate on the importance of the work or suggest applications and extensions. Do not cite references in the conclusion. Note that the conclusion section is the last section of the paper to be numbered. The appendix (if present), funding information, other acknowledgments, and references are listed without numbers.

Appendix

An Appendix, if needed, appears **before** research funding information and other acknowledgments.

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