TOPOLOGY OF SUPersonic JET Interaction
Flowfields at HIgh PRESSure RATIOs

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ABSTRACT: The flow structure of a jet at high pressure issuing normally from an orifice in a flat plate into a supersonic stream was examined using a Reynolds-averaged Navier-Stokes solver. The study confirmed the presence of secondary horseshoe vortices as well as identified new vortical structures that emanated downstream of the jet.

1 Introduction
The jet issuing normally from an orifice into a supersonic stream produces a complex three-dimensional flowfield, sometimes known as jet interaction (JI), which is rich in topological features. Some similarity exists between this flowfield and that induced by a cylindrical protuberance [1,2] that yields a so-called semi-infinite interaction [3], although the JI flowfield is further complicated by the interaction of two gas streams. The general near-field features of a JI are shown in Fig. 1 for a jet with a jet pressure ratio above unity [4]. The normal jet appears to be a blunt object to the incoming flow which produces a bow shock. This shock induces a three-dimensional, boundary layer interaction with a characteristic λ-foot shock structure and strong horseshoe vortices from vorticity creation via stretching of the vortex lines and baroclinic torque. The expanding jet is deflected by the main flow and a further shock, known as a barrel shock, is created. Vorticity creation within the jet produces a set of counter-rotating jet vortices which dominates the downstream flow. In addition, a reattachment shock is observed near the surface, downstream of the orifice.

The flowfield structure described above is primarily obtained from experimental observations using shadowgraphy and laser light screen and was also guided by subsonic observations [5]. This flow continues to remain to be a topic of great interest, with recent studies utilizing nonintrusive flowfield mapping and large eddy simulations to provide extremely detailed...
Technological interest in JI centers primarily on fuel injection into scramjet combustors [6–12] and in aerospace vehicle control [13–21]. This paper is concerned with topological features that arise at the high nozzle pressure ratios when JI is used for vehicle control purposes at high altitudes. It is well known that three-dimensional flows can possess a fascinating variety of topologies [22], the study of which dates to Poincaré in the late nineteenth century. For a long while, attention was placed primarily on surface topologies, particularly in high-speed aerodynamics, due to the difficulties of describing off-surface topologies in gaseous flows with its high level of diffusion or in the inherent unsteadiness at high Reynolds number. However, the ability to perform instantaneous or time-averaged flowfield mapping and computations have allowed detailed flowfield topologies to be revealed [23–26]. The present study reports new time-averaged features that observed through a parametric series of three-dimensional, Reynolds-averaged Navier-Stokes computations at various Mach numbers. There may be concern that flow unsteadiness, especially in the downstream region of the JI, may be important in understanding the physics of JI. Within the scope of this paper, this concern is obviously not addressed. However, the visualizations presented here provide details that hitherto have not been observed and thus represent a step toward a better understanding of the physics of JI.

2 Method

2.1 Governing Equations and Numerical Approach

The Reynolds-averaged conservation equations are solved numerically using a finite-volume scheme. The conservation equations are discretized using a first-order forward difference operator for the time derivative and a second-order central difference operator for the viscous terms. The Van Leer MUSCL upwind extrapolation is used for determining the face properties. Roe’s flux splitting method is used for the inviscid flux terms. A two-equation $\kappa - \kappa l$ is used to model the turbulence [27]. The numerical model was validated against [28]. Further details, including a mesh refinement study and a discussion on convergence of the numerical solution, can be found in [29].

2.2 Configuration and Flow Conditions

The configuration comprised of a 457.2 mm square plate with a jet orifice, 2.54 mm in diameter, located on the centerline at 177.8 mm from the leading edge. The coordinate system is located at the center of the orifice, with $x$ in the downstream axial direction, $y$ in the normal direction and $z$ in the spanwise direction. The orifice forms the exit of a convergent nozzle. The total pressure of the jet that leaves the nozzle is set by the pressure ratio. The results discussed are obtained at Mach 2, with others obtained at increments of Mach 0.5 to Mach 4.5, see Table 1. The total temperature for the freestream or jet is 244 K. Adiabatic conditions are assumed for the flat plate. The Reynolds number was set at 6.56 million per m for the entire study. To maintain a constant Reynolds number and total temperature requires that the pressure be varied, as is evident in Table 1. After the pressure is determined, the jet pressure ratio

$$PR = \frac{p_0}{p_\infty}$$ (1)

which is the jet total pressure normalized by the freestream pressure, is also fixed at values ranging from 5 through 2000. Jet interactions at very high pressure ratios have not been
previously examined in detail and are of interest in the present study. Table 1 also lists the momentum flux ratio, defined as

\[ J = \frac{\gamma_{j} p_{j} M_{j}^{2}}{\gamma_{\infty} p_{\infty} M_{\infty}^{2}} \]  

(2)

Since the jet is air and the orifice is choked,

\[ J = \left(1 + \frac{\gamma - 1}{2}\right)^{-\gamma/(\gamma-1)} \frac{PR}{M_{\infty}^{2}} \]  

(3)

However, due to viscous effects that resulted in a vena contracta near the jet exit, the Mach number at the exit is not uniform and its average value is 1.15 for all the cases studied. This resulted in about a 15 percent underestimate in the value \( p_{j} \) and \( J \). This underestimate is not significant for the present study which considers a wide range of \( J \) from 0.88 through 322. Finally, the flow is assumed to be turbulent from the leading edge. This assumption is not expected to result in errors in the JI phenomenon under investigation.

**Table 1. JI cases examined.**

<table>
<thead>
<tr>
<th>( M_{\infty} )</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{\infty}, \text{kPa} )</td>
<td>9.85</td>
<td>7.87</td>
<td>6.56</td>
<td>5.62</td>
<td>4.92</td>
<td>4.38</td>
</tr>
<tr>
<td>PR</td>
<td>5</td>
<td>15</td>
<td>100</td>
<td>500</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>( J )</td>
<td>0.88</td>
<td>2.64</td>
<td>17.6</td>
<td>87.9</td>
<td>176</td>
<td>322</td>
</tr>
<tr>
<td>( V_{j}, \text{m/s} )</td>
<td>303</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3 Results and Discussion

#### 3.1 Surface Topology

To simplify the discussion, the skin friction topology will be examined first. The skin friction lines together with surface isobars for the cases examined at Mach 2 are shown in Fig. 2. Consider first the low \( PR = 5 \) case of Fig. 2a. The incoming surface flow encounters the obstacle posed by the normal jet and an open separation, labeled “global lines of separation” ensues [22]. Topological rules dictate the presence of a saddle point followed by an attachment node. Figures 2b–f show the same upstream surface topology but with the features spread further apart. The spread in the spanwise direction is larger than in the upstream direction.

While the upstream surface features appear to be the same but further spread out despite the large variation in jet pressure ratio, the downstream surface flow shows distinct changes mostly via a downstream stretching of the distances between the singularities. For the low \( PR = 5 \), three saddle points and a pair of foci of separation occur near the rear of the orifice. As the jet pressure ratio increases, the rear pair of saddle points is pushed further downstream and an attachment node is observed. Note that the rear saddle point near the orifice remains fairly close to the orifice, but the other saddle point moves downstream and another saddle point along with an attachment node appear. A global line of separation in the downstream surface flow is also observed.
Fig. 2. Skin friction lines with surface isobars at Mach 2.
3.1 Flow Field Features

The surface topology does not fully reveal the complexity of the flow field, especially in the downstream region when the pressure ratio changes. For illustrative purposes, the salient flow field features for the Mach 2, $PR = 15$ case are shown in Fig. 3. Figure 3a shows an upstream $\lambda$-shock structure that arises from a shock/boundary layer separation. This separation results in a primary horseshoe vortex system that wraps itself around the jet which then trails downstream, as seen in Fig. 3b.1 The primary horseshoe vortices are associated with the global line of separation. A small secondary vortex is also identified in Fig. 3a between the shock and the jet that had not been well identified by previous computations [10,19,20] although Roger and Chan [30] mentioned a characteristic double horseshoe vortex structure in front of the jet which proceeds around and downstream. Nonetheless, the present study shows that the secondary horseshoe vortices are blocked by the primary horseshoe vortices from the surface (Figs. 3b and c). This is thought to be why the secondary vortices are not captured by surface flow visualizations. Further, the secondary horseshoe vortex can become a significant feature when the PR is large.

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1The primary horseshoe vortex is sometimes considered to be a pair of counter-rotating vortices, which is adopted presently.

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This is illustrated in Fig. 4 for $PR = 2000$, where the primary horseshoe vortex is shown in the left and the secondary horseshoe vortex is shown in the right. For a proper scale between the two subfigures, refer to the size of the jet orifice between them. It can be seen that the secondary vortex occupies a large vertical portion of the upstream interaction flowfield. The secondary horseshoe vortices also become more distinct with increasing jet pressure ratio, becoming a significant feature of the flowfield. This can be seen by a comparison between Figs. 3c and 4b for $PR = 15$ and 2000 respectively.

Downstream features are shown in Fig. 5. The jet vortices shown schematically in Fig. 1 are revealed in Fig. 5a. The simulations show that the jet and secondary vortices are intertwined, which may be why the secondary vortex was not previously revealed in experimental flow visualizations.

New downstream features are revealed in the present study. These include horn, near-field and far-field vortices, seen in Figs. 5b–d, respectively. The streamlines wrapping around the dividing surfaces emanating from the global separation lines formed into horn vortices which are small features just downstream of the orifice. These horn vortices are distinguished from the wake vortices, which have been reported in the past but not well understood either [14]. The present study shows that the wake vortices remain close to the surface and persists to the end of the computational domain.

4 Conclusions

Visualizations of time-averaged solutions of a jet issuing normally into a supersonic stream confirmed features that have been observed previously. In addition, the present study showed the existence of a secondary horseshoe vortex pair that intertwined itself with the jet vortices. The secondary horseshoe vortex pair remained within the flow and thus did not leave a footprint in surface visualizations. The study also revealed the presence of horn vortices just downstream of the orifice that were engulfed by the jet vortices. In addition, surface hugging wake vortices persist toward the exit of the computational domain.

References

a. Jet vortices emanating from the orifice.

b. Horn vortices at the rear of the jet.

c. Near-field wake vortices.

d. Far-field wake vortices.

Fig. 5. JI downstream flowfield features at Mach 2, $PR = 15$.


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