Flow features around double cones at hypersonic speed

R. Gomes-Fernandes
r.g.fernandes@imperial.ac.uk
Department of Aeronautics, Imperial College London
London, UK

ABSTRACT

An experimental study of double cone geometries in hypersonic flow (at M_∞ of 8·2 and Re_d of 0·36 $\times 10^6$) was performed to provide additional data to a computational simulation study. In this study, depending on how the flow was initialised, the numerical solution yielded a violent pulsation mode of instability or a steady flow. Finally, an analysis of the shock oscillation was made and discussed.

NOMENCLATURE

d model diameter
M Mach number
P pressure
r radius of curvature of the model shoulder
Re Reynolds number
T temperature
U flow velocity
x horizontal distance from the model base (see Fig. 3)
y vertical distance from the model axis (see Fig. 3)
ρ flow density

Subscripts

0 isentropic stagnation condition
d model diameter
∞ free stream conditions

Paper No. 3896. Manuscript received 3 August 2012, revised version received 29 January 2013, accepted 3 February 2013.

https://doi.org/10.1017/S000192400000840X Published online by Cambridge University Press

1.0 INTRODUCTION

Panaras and Drikakis[1] examine the effect of flow initialisation on the numerical prediction of flow around spiked blunt bodies. Of the two schemes used only one predicted the experimentally observed behavior. The schemes used were the 'uniform-unsteady condition' (UUC) and the 'steady-feeding-unsteady' (SFU). The former consists in initialising the flow variables to a uniform flow field based on the free stream conditions and applying the unsteady solver from the beginning of the simulation. The latter is based on an approximate steady-state solution which is obtained by applying the steady solver.

Two of the models used (Fig. 1) had been tested by Panaras[2] at $M_\infty = 6{\cdot}0$ and $Re_d = 0{\cdot}12 \times 10^6$. Schlieren pictures showed that a steady flow developed with separation near the spike tip and reattachment on the rounded shoulder of the body, for both shapes. In contrast, one of the computational schemes predicted a strong longitudinal pulsating flow whilst the other agreed well with experiment.

To provide additional data, the same two models were tested at $M_\infty = 8{\cdot}2$ and $Re_d = 0{\cdot}36 \times 10^6$ in the Cranfield University gun tunnel and Schlieren images were recorded with a high speed digital camera operating at about 4,000 frames per second.

2.0 EXPERIMENTAL PROGRAMME

2.1 Wind tunnel and flow conditions

The models were tested in the Cranfield University gun tunnel (for details see Lanson and Stollery[3]) at a M_∞ of $8{\cdot}2 \pm 0{\cdot}05$ and Re_d of $0.36 \times 10^6 \pm 7{\cdot}6\%$. The general flow conditions can be seen in Table 1.

2.2 Models

The double cones are shown in Fig. 1. Conic 1 has cone angles of 10° and 70° and radius of curvature at the shoulder of the second cone of $r = 0{\cdot}2d$. Conic 2 has cone angles of 19° and 70° and the same radius of curvature at the shoulder as Conic 1.

Table 1
Experimental test conditions

Gun Tunnel Details	
M_∞	$8{\cdot}2 \pm 0{\cdot}05$
Driver Pressure (atm)	137
$P_{0,\infty}$ (Pa)	$108{\cdot}9 \times 10^5 \pm 1\%$
P_∞ (Pa)	$950 \pm 1\%$
$T_{0,\infty}$ (K)	$1{,}290 \pm 3\%$
T_∞ (K)	$89{\cdot}3 \pm 3\%$
ρ_∞ (kg/m^3)	$0{\cdot}0371 \pm 7{\cdot}1\%$
U_∞ (ms^{-1})	$1{,}553 \pm 1{\cdot}6\%$
Re_∞/cm (cm^{-1})	$9{\cdot}01 \times 10^4 \pm 7{\cdot}6\%$
t_{run} (ms)	$31 \pm 0{\cdot}5$

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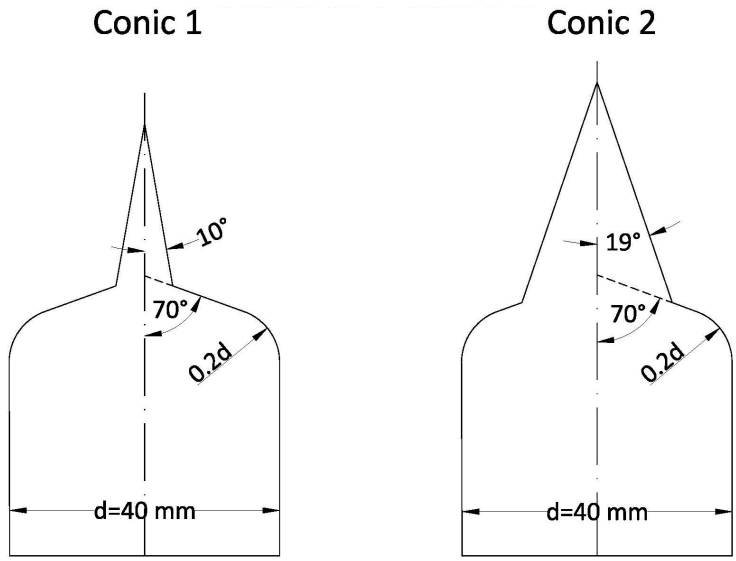


Figure 1. Double cones geometry.

2.3 Schlieren system

A Schlieren system was used in a *z*-type configuration according to Estruch *et al*[4]. A LED light source was used in a continuous mode and in combination with direct imaging onto a Photron APX high speed digital camera. The frame rate at which the camera operated was 4,000 frames per second with an image size recorded of 1,024 × 512 pixels.

2.4 Schlieren image processing

The shock wave unsteadiness was measured from the Schlieren images using the method described in Estruch *et al*[5]. Briefly, this method consists of reading the test images into two-dimensional matrices where each position represents the pixel intensity on a greyscale. The background image is subtracted from the test images in the frequency domain to reduce noise and improve accuracy. Finally, an edge detector algorithm is applied to the images in the spatial domain.

The rationale behind this method is that shock waves are characterised by a sharp gradient in terms of density. This phenomenon appears in the Schlieren pictures as a dark region in the upper half and a bright region in the bottom one (see Fig. 2). Therefore, it is possible to detect the shock wave location by applying an image edge detector such as the Canny algorithm. This detector is used with a suitable threshold to detect the highest intensity gradients in the image, thus, isolating the shock waves.

It is important to emphasise that the Schlieren system averages the density gradients across the test section. This fact can affect the images if the flow has important three-dimensional effects.

3.0 RESULTS AND DISCUSSION

3.1 Flow pattern

A sample of Schlieren pictures of the present study are shown in Fig. 2.

The flow around Conic 1 is not completely steady as it is noticeable very small movements of

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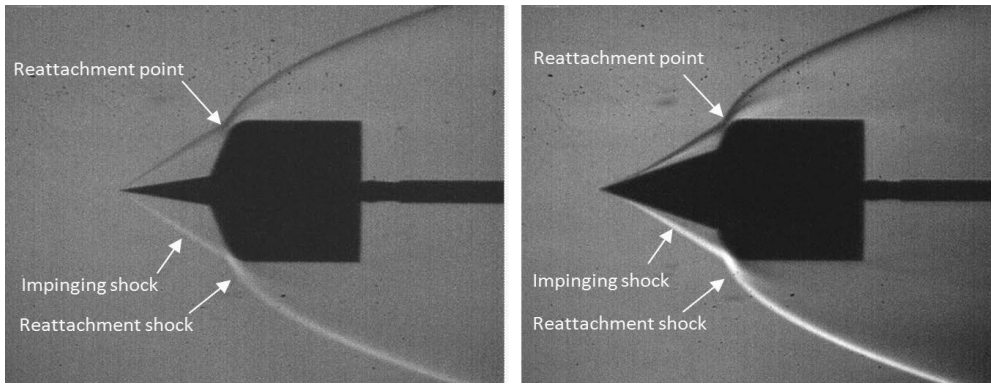


Figure 2. Schlieren images from the experiments of the present study on Conic 1 (left) and Conic 2 (right) at M_∞ = 8·2 and Re_d = 0·36 × 10^6.

the reattachment point. For Conic 2 the variation of the reattachment point position was more marked and modest lateral fluctuations of the separated flow were visible.

In terms of the computational simulations performed by Panaras and Drikakis[1], it was expected that both methods of flow initialisation would lead to the same results. However, this was not the case for Conic 1 as the UUC procedure led to the development of a strong pulsation mode of instability while using the SFU procedure the shock appeared steady. The pulsation mode is one type of shock wave instability that was first reported by Mair[6] and it is explained in detail by the simulations of Feszty *et al*[7].

The present experimental results show no pulsation cycles of instability in the Conic 1 model unlike the computational results using UUC initialisation. Nevertheless, it was noticeable, for both Conic 1 and 2 models, a small amplitude oscillation both at the impinging and reattachment shocks. The study of these oscillations is presented in detail in the following section.

3.2 Shock unsteadiness

In order to assess the level of shock unsteadiness around the double cones the shock oscillation was measured along two different lines A and B (Fig. 3), in the impinging and in the reattachment shocks, respectively.

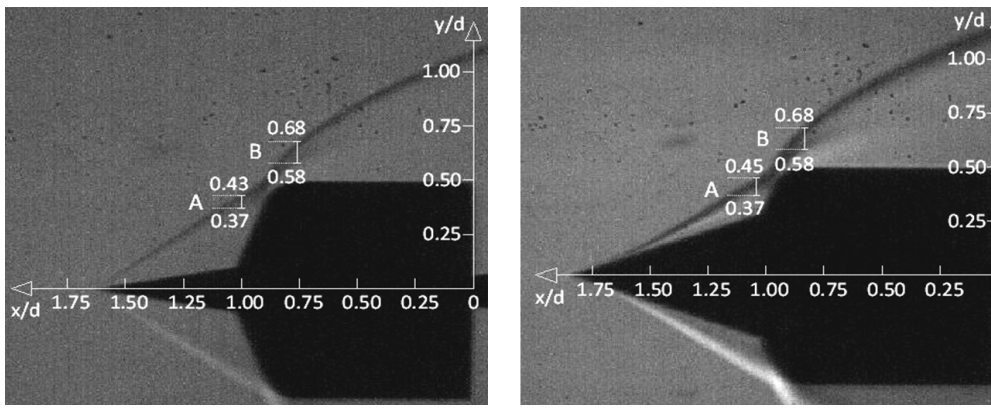


Figure 3. Location of the lines where the shock unsteadiness was measured in Conic 1 (left) and Conic 2 (right). The numbers above and below lines A and B are the boundaries of those lines in terms of *y/d*.

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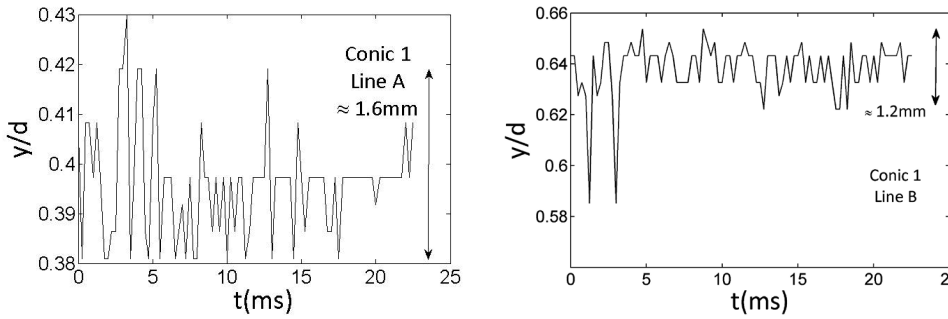


Figure 4. Shock oscillation along line A (left) and B (right) in Conic 1.

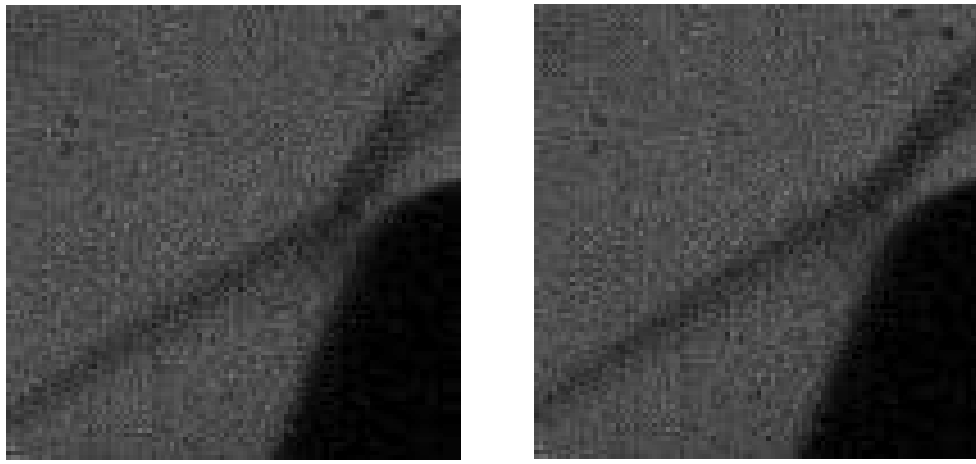


Figure 5. Flow development around the upper shoulder of Conic 1 (time increment of 15·5ms between the images).

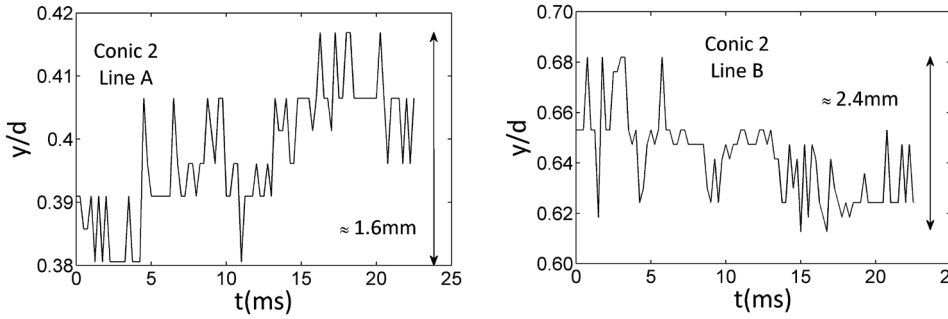


Figure 6. Shock oscillation along line A (left) and B (right) in Conic 2.

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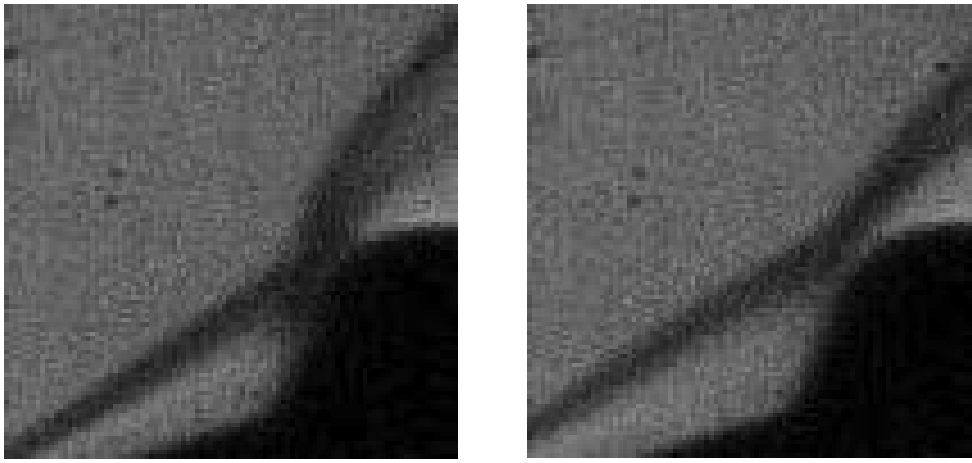


Figure 7. Flow development around the upper shoulder of Conic 2
(time increment of 14·5ms between the images).

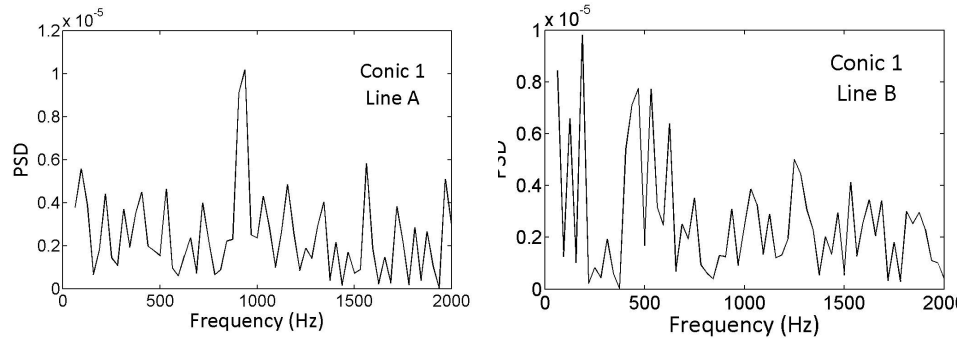


Figure 8. Power spectrum of the shock oscillation along lines A (left) and B (right) in Conic 1.

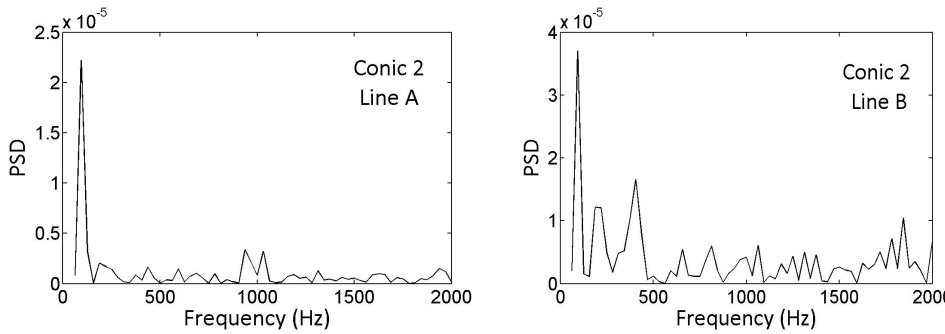


Figure 9. Power spectrum of the shock oscillation along lines A (left) and B (right) in Conic 2.

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Figure 4 to Fig. 7 show the results of the shock displacement along the aforementioned lines. Data for $t \geq 0$ was taken after the initial unsteady flow, characteristic of this type of gun tunnels, disappeared. It is possible to see from these Figures that the shock waves are not completely steady but the movements are very small. Therefore, for the conditions tested in the experiments, it is possible to conclude that there is definitely not a pulsation mode of instability but neither is the flow completely steady. These small changes might happen due to the non-uniformity of the flow or the roughness of the model's material, for instance. Nevertheless, it is not clear why they happen.

In terms of the behaviour of the displacements, it is possible to see that they are different for the two models. While in Conic 1 it seems that the shock oscillates centred in a defined value, in Conic 2 the shock seems to oscillate centred in values that change in steps. This fact is very clear when looking at the shock oscillations power spectra for both models in Figs 8 and 9 and when the Schlieren pictures of the flow are seen in sequence. The power spectra were obtained using a fast Fourier transform algorithm of the shock displacement time series.

For the Conic 2 model the dominant frequencies are very low, around 100Hz, as expected for the step behaviour of the shock oscillation. On the other hand, for Conic 1 there seems to be no dominant frequency for the reattachment shock and a spike frequency of around 900Hz for the impinging shock.

4.0 CONCLUSIONS

The flow past the double cones (captured by Schlieren pictures recorded at 4,000 frames per second) did not reveal any sign of the pulsation mode of instability. This is in contrast to what the computational results from Panaras and Drikakis[1] predicted using the Uniform-Unsteady Condition (UUC) flow initialisation procedure. On the other hand, a mild shock oscillation was captured and an estimation of the shock displacement showed that the flow was not entirely steady.

For the present case, the Steady-Feeding-Unsteady (SFU) flow initialisation procedure used by Panaras and Drikakis[1] provided the computational solution most similar to the experimental results.

Panaras and Drikakis[1] acknowledged in their concluding remarks that experimental evidence showed 'oscillations of very small amplitude in the reattaching part of the flow'. The magnitude of the oscillations was not reported but the description matches that found experimentally in the present study.

The oscillations appeared to be self-sustained and their origin could be object of a computational research, serving as a good code validation case. The degree of pressure and heat fluctuation could be experimentally studied in order to assess their importance to the overall flow.

The present experiments support those of Panaras[2] and emphasise that, in computational calculations, the present type of flow development depends strongly on the assumed initial conditions which must be chosen carefully if accurate predictions are to be made.

ACKNOWLEDGEMENT

I wish to dedicate this paper in memory of Prof John Stollery and to express my gratitude for his encouragement and support to submit this work. Thank you also to Dr David Estruch-Samper for the help with the experimental setup.

https://doi.org/10.1017/S000192400000840X Published online by Cambridge University Press

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