Refereed Article

High-speed imaging of dynamic shock wave reflection phenomena

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Abstract
Dynamic shock wave reflection generated by a rapidly pitching wedge in a steady supersonic free stream has been studied with numerical simulation previously. An experimental facility was developed for the investigation of these dynamic phenomena in a supersonic wind tunnel at the Council for Scientific and Industrial Research (CSIR), South Africa. This paper documents details of the experimental setup and presents results from dynamic tests. High-speed schlieren images of the dynamic flow field were captured with a Photron Ultima APX-RS high-speed camera at 10,000 fps. Results are presented for tests at Mach 1.93 and Mach 2.98 free stream conditions.

Keywords: dynamic shock wave reflection, high-speed imaging, schlieren

1. Introduction

Consider the shock wave reflection pattern generated by a steady wedge of infinite span in close proximity to an ideal wall in a supersonic free stream. The steady two and three shock configurations possible (Fig. 1) in a supersonic free stream, under these conditions, are well known as well as the transition between these configurations.[1] Transition criteria for the steady, two-dimensional case are derived by consideration of local flow conditions at the reflection point and were published by Ben-Dor.[2] This problem has been investigated extensively in the last 130 years since the early experiments by Ernst Mach in 1878. However, there has been little investigation on the dynamic effects generated by a rapidly pitching wedge.

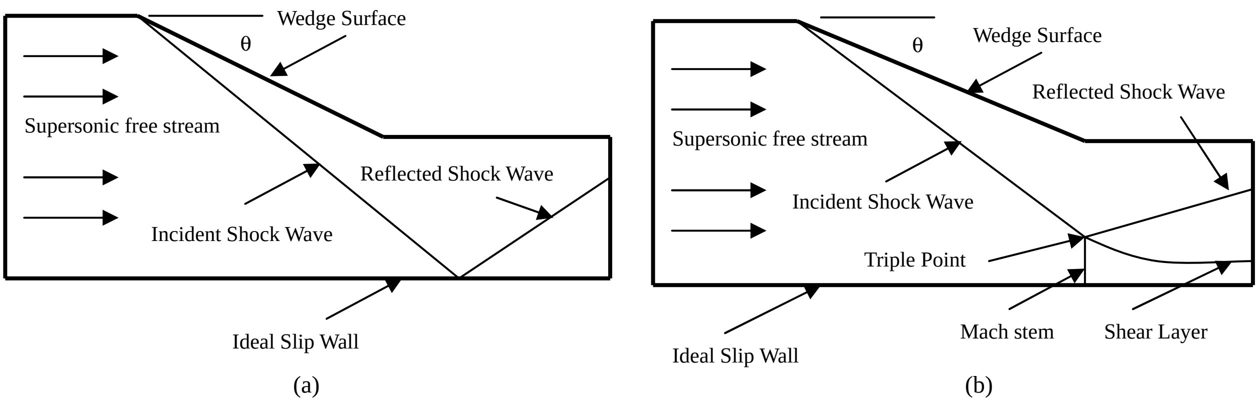

Fig. 1. (a) Regular reflection (RR) and (b) Mach reflection (MR).

Felthun and Skews[3] as well as Naidoo and Skew[4] proved with numerical simulation, that the dynamic effects due to rapid rotation of the wedge result in an unsteady flow field in which the steady state transition criteria are not valid. Numerical results proved that it was indeed possible to achieve transition from RR to MR beyond the theoretical steady criteria with a rapidly pitching wedge (Fig. 2). This was an important and fundamental finding in shock wave physics. Pitch rates that were used in the simulations resulted in wedge tip speeds up to 10% of the free stream acoustic speed. The wedge was started impulsively (with an initial, established steady RR) and rotated at a constant rotation rate.

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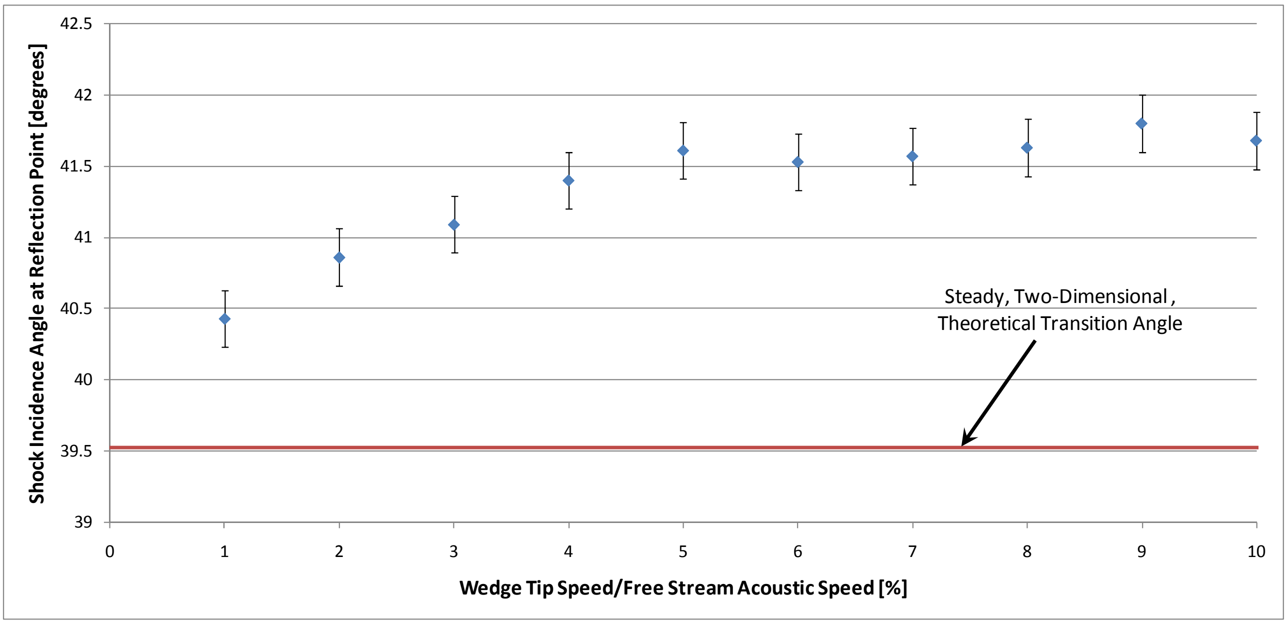

Fig. 2. Dynamic effect on shock incidence angle at transition predicted by Felthun and Skews[3] in a Mach 3.0 free stream.

Subsequently, an experiment was designed by the authors to validate this result. In a conventional blow-down supersonic wind tunnel at Mach 3.0, using air at 300.0 K, with a wedge chord of 40.0 mm, this required starting the wedge impulsively and rotating it at a constant rate of 29,723 deg/s. Evidently, the validation of this type of numerical simulation with an experiment is a challenging one. A unique experimental facility was developed at the Council of Scientific and Industrial Research in South Africa and tests were completed successfully. The results provide conclusive experimental evidence to support the dynamic effect presented by Felthun and Skews[3] and Naidoo and Skews.[4] This paper presents a brief description of the facility, high-speed images from dynamic experiments and results from analysis of images.

2. Experimental setup

2.1 Supersonic wind tunnel facility

A rig was designed for the supersonic wind tunnel facility at the Aeronautics Programme at the Council for Scientific and Industrial Research (CSIR) in South Africa. The blow-down wind tunnel consists of a 450 mm×450 mm test section and has a free stream speed range between Mach 0.6 and Mach 4.3. Maximum available blow times range between 15 to 30 seconds depending on free stream conditions.

2.2 Experimental rig

In an experiment, the ideal slip wall or reflection plane shown in Fig. 1 may be generated with a symmetric double wedge configuration. The symmetric arrangement of the wedges about a horizontal image plane sets up a perfectly rigid, frictionless, adiabatic wall as seen in Fig. 3. This ensures that the reflection is not contaminated by a boundary layer that would develop on a surface in the tunnel. The rig consists of two large aspect ratio wedges arranged and actuated symmetrically about a horizontal reflection plane (Fig. 4).

Each wedge (chord, w = 40.0 mm) has an aspect ratio (span to chord ratio) of 4.25 to ensure two-dimensional transition in the vertical wedge centre plane at the free stream conditions considered in this experiment. Skews[5] proved that transition between RR and MR in the wedge centre plane approaches the steady, theoretical prediction, provided the wedge aspect ratio is above a critical value. An aspect ratio of 4.0 is sufficient to ensure two-dimensional RR to MR transition in this case.

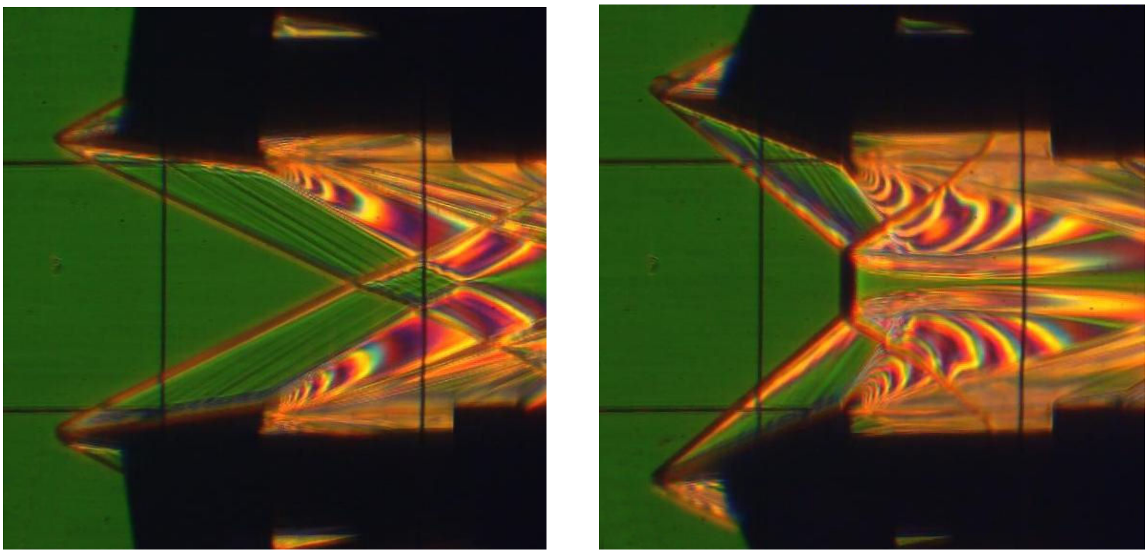

Fig. 3. Schlieren images of RR and MR setup with a steady double wedge configuration in a Mach 3.0 free stream.

The wedges may be pitched at small rotation rates with a servo-driven actuator, for the steady state experiments, and at larger pitch rates with a spring energized actuator to generate the required dynamic phenomena. The servo-driven actuator changes the wedge incidence gradually at approximately 5.0 to 10.0 deg/s. This is sufficiently small to ensure a steady flow field as the wedge pitches. High-speed images and results of the steady experiment were presented at the 28th ICHSIP.[6]

The actuator for the dynamic experiment energizes a spring system with approximately 1000N. The tunnel and rig are operated remotely by a test team. At tunnel startup the wedges and spring system are locked with a custom designed latch system. The latch is released with an electric motor and this enables remote operation. After the flow stabilizes at tunnel startup, the spring system is released and the wedges execute a pitch range of approximately 20 to 30 degrees in about 6 ms. The resultant motion is also influenced by the aerodynamic forces on the wedge surface. Depending on the tunnel free stream condition, a maximum instantaneous rotation rate between 8,000 to 11,000 deg/s may be achieved. Though it was not possible to achieve larger accelerations with this actuator, it was sufficient to generate a measurable dynamic effect. A previous, unsuccessful, version of the rig was designed to achieve between 20,000 to 30,000 deg/s in the required pitch range. This was considerably larger and prevented tunnel startup due to the excessive blockage. Due to the actuator forces it also raised concerns of safety during operation and was abandoned.

Fig. 4. Experimental rig for the investigation of dynamic shock reflection phenomena.

Before each test, the camera was pre-set on the “centre” recording mode. Image capture was triggered manually by a camera operator. In a test, after the tunnel flow stabilised and a steady initial flow pattern was established, the rig operator released the latch remotely. The latch release control unit alerted the rig and camera operator of the release with an LED signal and image capture was triggered. The total event was only 6.0 ms and the acquisition system was able to record a 2.5 s event with the available onboard memory. There were no issues with timeous triggering and image capture.

2.3 Flow visualization

Flow visualization was achieved with a standard z-type schlieren system[7] and high-speed imaging was done with a Photron Ultima APX-RS. High-speed images recorded with the Photron from the steady state tests were recorded at 250 fps and presented at the 28th ICSHIP.[5] The dynamic tests were not completed before the 28th ICSHIP due to the failure of the latch mechanism at tunnel startup. Subsequently, the dynamic tests were completed. Images were captured at 10,000 fps with a $^{1}/_{30000}$ s exposure time. Maximum image resolution at this frame rate is 512×512 pixels. A calibration grid (5 mm×5 mm spacing) was used to correct image co-ordinates for any distortion in the image. The measurement of co-ordinates with this system proved to be very accurate. The orientation of a line on the image may be measured within 0.2 degrees and the distance between two points may be measured within ± 0.2% of the wedge chord. Considering that the dynamic effect of interest is of the order of magnitude of 1.0°, the accuracy is crucial to the investigation.

3. Results for dynamic RR to MR transition

In this particular experiment a steady RR was established at a wedge incidence of approximately 2.2°. The latch was released and the wedge pitched until the wave system disgorged as shown in Fig. 5 (h). In Fig. 5 (b) a shear layer has developed close to the symmetry plane. This indicates that transition to MR has occurred, though this may not be the exact instant of transition. As the wedge accelerates further the Mach stem grows until the reflected wave intersects the wedge surface. The wave system disgorges shortly after the reflected wave intersects the wedge surface. The entire pitch motion lasts approximately 5.4 ms. The exposure time was sufficiently short to capture a sharp shock front, even though the wave system is advancing at a rapid rate. The physics of primary interest occurs between transition to MR and the time before the wave system disgorges, viz. the 8 frames between 3.6 to 4.4 ms. The Photron Ultima APX-RS is able to record images at maximum resolution (1024×1024 pixels) up to 3000 fps. If images were recorded at this frame rate for maximum image resolution, images would be double the resolution of the current image set, but there would only be 2 to 3 frames beyond transition. It was also possible to capture images faster than 10,000 fps, but the reduced resolution would result in a higher uncertainty on the wave angle measurements.

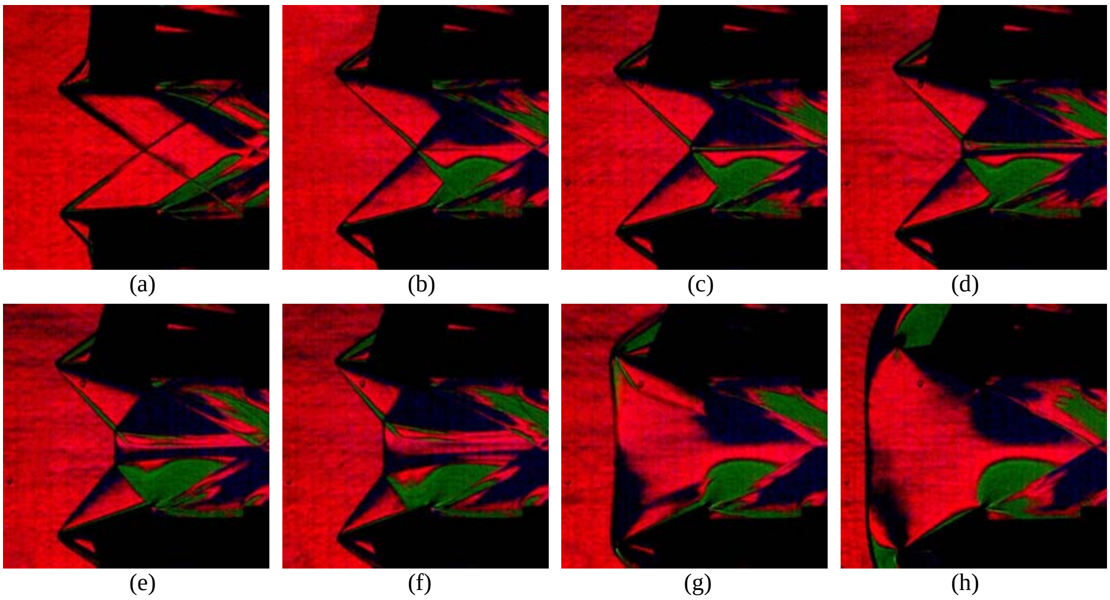

Fig. 5. Evolution of dynamic RR to MR at Mach 1.93 : (a) T = 0.0 ms, (b) T = 3.6 ms, (c) T = 3.8 ms, (d) T = 4.0 ms, (e) T = 4.2 ms, (f) T = 4.6 ms, (g) T = 4.9 ms, and (h) T = 5.4 ms.

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Wedge incidence, shock incidence and Mach stem height, m, were measured from each image as illustrated in Fig. 6. A linear fit of 6 points on each line was done and gradients were calculated. The Mach stem height was determined by halving the distance between both triple points. Shock incidence at transition was determined by extrapolating the Mach stem growth data in Fig. 7 (b). The measured wedge motion (Fig. 7 (a)) was used as input to a flow simulation.

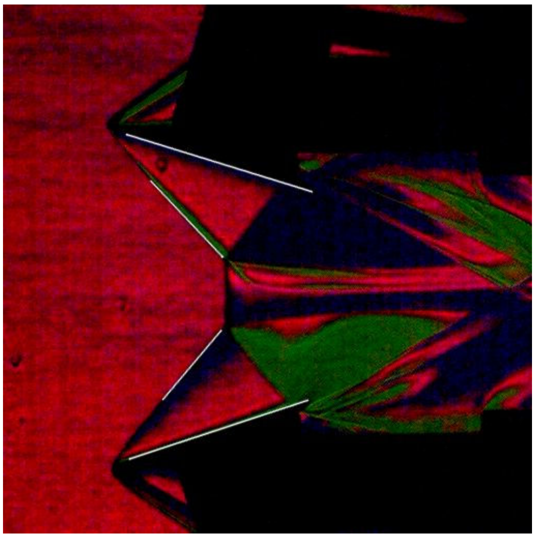
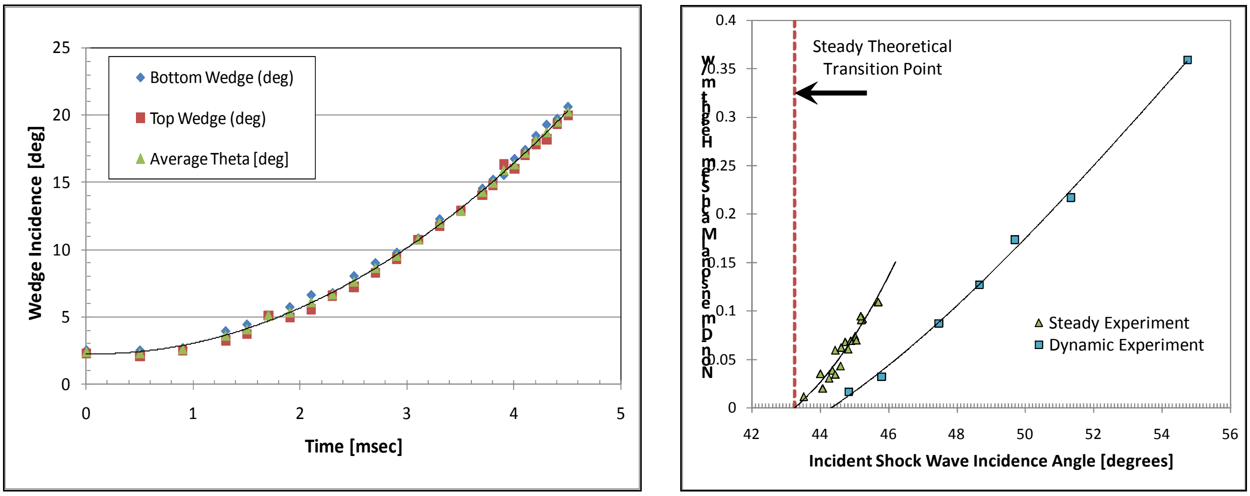


Fig. 6. Sample process to determine shock incidence, wedge incidence and Mach stem height.

Transition was observed at 44.3° in the experiment and simulation, approximately 1.0° beyond the steady state criteria (Fig. 8). Considering that the previous results published by Felthun and Skews[3] and Naidoo and Skews[4] used the same simulation method, the agreement between experiment and simulation supports the predictions previously made. Experiments were also executed at Mach 2.98. Tests for decreasing incidence were done at Mach 3.27 and Mach 2.96. Measured transition for all the dynamic experiments in comparison with steady theory and experiment are presented in Fig. 8.



(a) (b)

Fig. 7. Measurements from images. (a) Wedge incidence vs. time; (b) m/w vs shock incidence for steady and dynamic experiment at Mach 2.98.

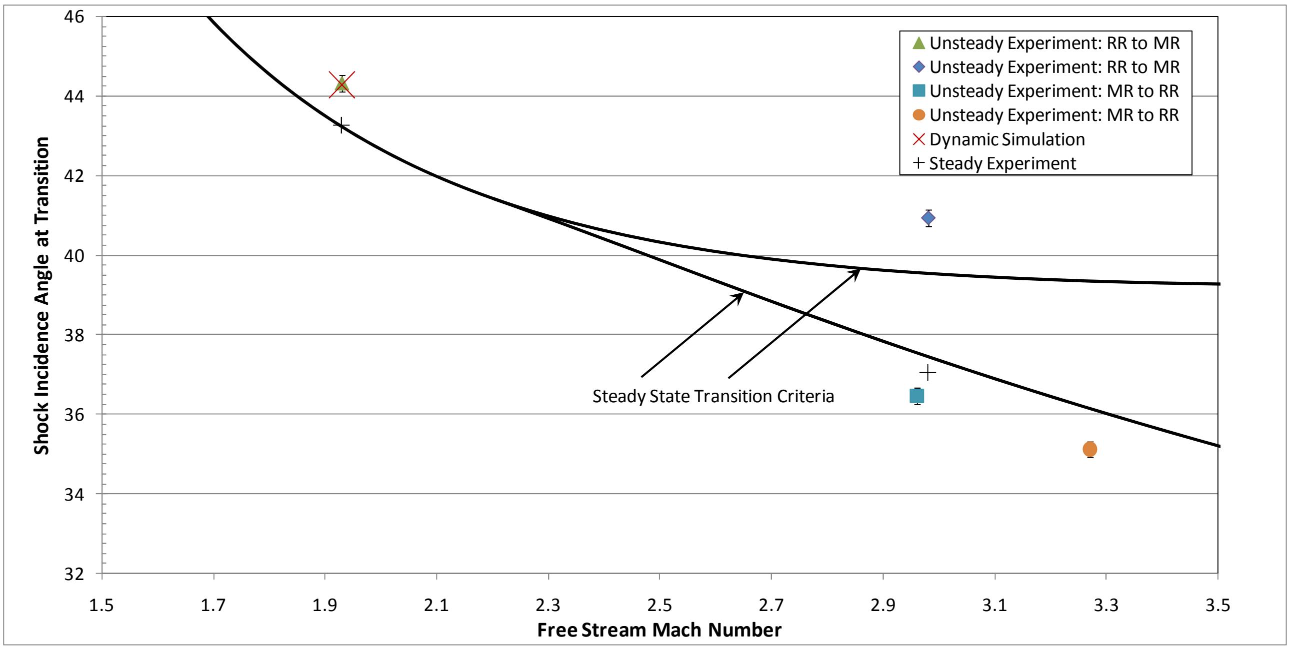


Fig. 8. Steady and dynamic measurements and simulation results against steady theory.

4. Conclusions

An experimental facility was developed to investigate the dynamic phenomena generated by a rapidly pitching wedge in a supersonic free stream. Analysis of high-speed images from a series of tests were done and showed significant deviation from the theoretical steady criteria. Simulation of an experiment produced excellent agreement. These results support the dynamic effects predicted previously. This is the first experiment to demonstrate transition beyond steady state theoretical limits and is a significant result in the field of shock wave physics.

Acknowledgments

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