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Free-flying Model Testing in the X2 Expansion Tube

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Abstract

Free-flying model testing is a common technique used in hypersonic impulse test facilities to measure forces over scaled models of hypersonic vehicles. While this technique is widespread in low enthalpy facilities and reflected shock tunnels where test times are generally of the order of milliseconds or longer, it has largely been unexamined in very high enthalpy hypersonic impulse facilities such as expansion tubes due to their much shorter test times of generally much less than a millisecond. Recent work in UQ's X2 expansion tube has aimed to change that by beginning free-flying model testing and validation in the facility. This paper will summarise previous and current free-flying model testing on UQ's X2 facility while also discussing new supporting techniques which are being developed, such as an off-axis parabolic schlieren system for model illumination and a pneumatically operated model release system.

Keywords: *expansion tube, shock tunnel, impulse facility, high-enthalpy testing, free-flying models*

1. Introduction

Expansion tubes are important test facilities for the study of planetary entry and high enthalpy hypersonic phenomena. They are used around the world to study entry into all of the planetary bodies in the solar system, to study highly hypersonic flow conditions where both high enthalpies and high total pressures are experienced at the same time, and for studying fundamental processes seen in highly hypersonic flow such as finite rate dissociation and ionisation phenomena and flow radiation.

One of the limitations of expansion tubes is that they have test times generally an order of magnitude shorter than similar sized reflected shock tunnel facilities. This means that while high-speed optical tracking of free-flying models has become a common and advanced testing technique for measuring forces in other types of impulse hypersonic test facilities such as reflected shock tunnels [1, 2, 3, 4, 5, 6, 7] and various forms of blowdown tunnels [8, 9, 10, 11], this has not occurred for expansion tubes.

Over the last several years, researchers at the University of Queensland (UQ) have started down the path of performing free-flying model testing in UQ's X2 expansion tube, where test times are generally of the order of $100\,\mu s$ [12]. Initial work by Page and James performed free-flying tests of a 3D printed projection of the front of an Apollo capsule in UQ's Drummond small reflected shock tunnel [13, 14]. The Drummond tunnel was used as a stand in for the X2 facility due to its similar Pitot pressure, scale, and test time. After these tests were successful, a second pass at the experiment was performed in X2 by Sharma [15]. In both cases, noticeable model movement of the order of several millimetres was achieved during the test time, showing that free-flying measurements over X2 time scales were possible.

This work was followed up by Wallington and James [16, 17], who tested a 3D printed free-flying European Space Agency (ESA) Intermediatate eXperimentation Vehicle (IXV) model in the X2 expansion

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tube, which weighed around 20 g and showed that, while the movement was minute (of the order of 1 pixel in the whole recording), with sub-pixel image analysis, such as that performed in the work of Laurence et al. [1, 2, 5, 6], model movement and accurate tracking was borderline but possible. Their subsequent theoretical work showed that lighter and blunter models would move more easily [18]. As suspected, this work also showed that measurements would be more suitable in larger expansion tubes such as UQ's X3 expansion tube [19, 20], LENS-XX [21], or HYPULSE [22], but still, X2 is an important test bed for developing techniques which could be applied to these larger facilities.

This paper highlights the work that has performed so far both in X2 and in UQ's Drummond tunnel to develop techniques for X2, a new schlieren system which has been designed for use in these experiments on X2, a model release system which has been designed and bench tested, and future opportunities which free-flying model testing and X2's unique capabilities will allow it to explore.

2. Previous Free-flying Model Testing in the X2 Expansion Tube

Free-flying model testing started in UQ's Expansion Tube Laboratory in 2018 after the first author of this paper saw a presentation by Hannemann et al. [4] at a conference in early 2017. Our belief was that if we could make the model light enough, and performed experiments using blunt models to maximise the forces, it might be possible to do free-flying model experiments in our X2 expansion tube, even with its limited test time of around 100 μs.

Preliminary experiments were performed by Page et al. [13, 14] in UQ's Drummond reflected shock tunnel, a small cold driven reflected shock tunnel at UQ which is generally used for teaching. While this would not provide the strong post-shock chemistry seen in an expansion tube flow, its conditions offer similar test times and Pitot pressures to most standard X2 test conditions (around 100 μs and 100 kPa respectively) making it a good facility to use for testing the feasibility of techniques which we later want to apply on the much busier X2 facility. While slightly unrealistic, the model tested was a thin, but solid, 3D printed, plastic, two-dimensional projection of the front of the Apollo capsule at the maximum size which could be tested in the Drummond tunnel. The model was imaged using the Drummond tunnel's standard schlieren system and a high-speed camera and was suspended from the roof of the facility with fishing line which was designed to hopefully break when the flow arrived. Different models were tested, which weighed from 0.8 to 7.2 g and visible model displacements of 2 to 5 mm were seen during the facility test time.

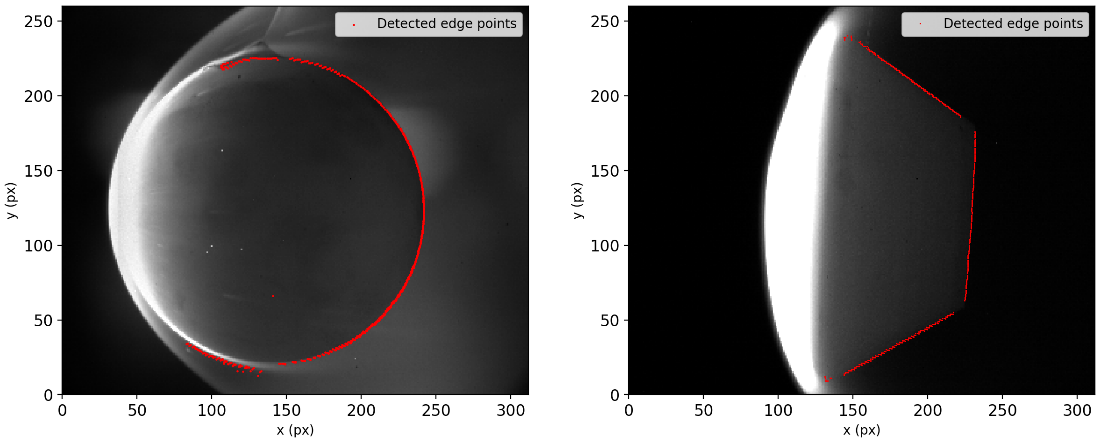
After this success a similar experiment was then performed in X2 itself by Sharma [15] who tested a similar model to Page et al. [13, 14] using one of X2's highest Pitot pressure, high enthalpy conditions, with a Pitot pressure of around 1 MPa. The model was a solid 3D printed model made using SLA resin, with a thickness of 2 mm and an estimated mass of 20 g (the exact model masses are not noted in the report). To perform a simple first test, the radiative emission from the high enthalpy flow stagnating over the front of the model was used to illuminate the front of the model for image tracking as opposed to using any kind of external light course. A Shimadzu HPV-1 ultra-high-speed camera was used, recording at 250 kHz. Once again, obvious model displacement was seen, with the model moving several millimetres during the facility test model and a total movement of around 12 mm seen during the full recording time of 200 μs, which includes some of the post-test time flow. The models generally survived the experiment but began to break up in the post-experiment flow. This work showed that this kind of testing was possible in X2 in select cases, even without the need for sub-pixel model tracking algorithms, showing that potentially more realistic cases could be studied using them in the future if needed.

In 2021 Sneath [23] attempted to model the results of experiments like Sharma's initial X2 free-flying model experiments [15]. He began the process of developing a sub-pixel resolution image tracking code like that used in Laurence et al. [1, 2, 5, 6] and generated artificial digital images which were moved and then used to test the tracking algorithm. To have high-quality data to test the algorithm with, sample data from the HEG shock tunnel in Germany from Friedl et al. [3] which was provided by one of the authors of that paper was also used.

In 2022, Wallington et al. [16, 17] attempted free-flying model testing in X2 using a more realistic model geometry, when they attempted to test a scaled-model of the ESA IXV wingless re-entry glider in X2.

The model was a hollow, plastic, 3D printed model which weighed $20\,\mathrm{g}$ and like Sharma's work [15] was backlit by the radiating, high enthalpy flow and a Shimadzu HPV-1 ultra-high-speed camera was used, recording at $250\,\mathrm{kHz}$. It was tested at a scaled test condition based on the trajectory point which was expected to maximise chemistry in the post-shock flow, meaning the chemistry was expected to have the largest effect on the forces to the vehicle [16, 17]. The goal of the experiments was to test different flap angles to see the effect that they had on the moment to the vehicle in free-flight. Six different flap angles were tested, including one angle which was artificially large to try to exaggerate the rotation. However, the differences in moment were hidden by the noise in the measurements as the model barely moved. Further analysis of these experiments after the fact in Wallington et al. [18] showed the experiment was just on the edge of the kind of image tracking which could be done in X2's test time using sub-pixel image tracking and that with shadowgraph or schlieren imaging to properly backlight the model, as is generally done when free-flying model force measurements are performed, and better placement of the camera window around the model, potentially measurements with lower uncertainties were possible for this geometry in X2. Overall though, Wallington et al. [18] showed that free-flying model testing on blunt-capsules was more suitable for an X2 sized facility due to the larger forces per unit area, that sub-pixel tracking was definitely needed for free-flight testing on X2, and that some kind of model illumination was needed so the whole model could be tracked, not just the front which was illuminated by the flow. These conclusions led to the sub-pixel tracking developed in Wallington et al. [18] which is briefly summarised here in Section 3 and the design of an off-axis parabolic schlieren system for X2 which is discussed here in Section 4. It also helped steer later experiments to blunter geometries which are more suited to X2 experimentation.

In 2023, several further free-flying model experimental campaigns were performed in our laboratory, with two example high-speed camera frames shown in Fig 1 below.



(a) free-flying sphere model used to optically measure Pitot pressure

(b) free-flying entry capsule model at $11\,\mathrm{km/s}$

Fig 1. Recent free-flying model experiments performed in the X2 expansion tube.

Edwards examined whether a free-flying spherical model with a known drag coefficient could be used to measure Pitot pressure in the facility [24]. A store-bought ping pong ball was used at the spherical test model, which was backlit with a bright blackbody light source (a halogen lamp), unlike the narrow bandwidth lasers and LEDs which are now the standard light sources used for optical free-flying model measurements in high enthalpy, radiating flows, as they can be used with a related narrow bandpass optical filter to help remove flow radiative emission from the optical measurements. A drag coefficient of 0.92 was assumed for the model, based on the highest enthalpy small sphere drag data we could find in the literature [25, 26], which along with the hypersonic Pitot pressure correction, the projected area of the model, and the experimental force measurement, can be used to ascertain the Pitot pressure of the flow. An example high-speed camera frame from one of Edwards' experiments can be seen in Fig. 1a below with a circle fit to the model for tracking. In the figure it can be seen that the halogen lamp has done a good job of illuminating the back half of the model, but not the front of the model at the stagnation point, where the flow radiation was the strongest. The initial results from this study were promising, but further testing with better illumination is needed, as well as simulations of the model for the particular test conditions so that a drag coefficient at conditions close to the real experiment can be found, instead of relying on a generic value from the literature.

A free-flying glider was tested, again in UQ's Drummond tunnel, by Bui in 2023 as well [27]. This project ended up being mainly concerned with the design and preliminary testing of a new off-axis parabolic schlieren system for X2, which was to be first tested on the Drummond tunnel before testing on X2. However, due to time constraints, X2 testing was not able to be performed. Preliminary Drummond tunnel results were very promising and are discussed further where the schlieren system is discussed in Section 4. This free-flying glider work will be continued in X2 or maybe our larger X3 facility in future years to make use of the longer test times available for model motion.

The final interesting result from 2023 was an experiment performed at $11\,\mathrm{km/s}$ in X2 where a white, plastic, hollow, free-flying, capsule model was tested to check if this type of force measurement could be used to verify some seemingly erroneous accelerometer measurements which had been performed on X2 during this same test campaign. An example high-speed camera frame from one of these experiments can be seen in Fig. 1b below. It can be seen that the model seems to be transparent to the radiating flow on the front, which has backlit the back of the model, allowing it to be seen. This was an interesting unexpected result.

3. Sub-pixel Resolution Optical Tracking

This section summarises some of the details of the X2 sub-pixel tracking routines developed in Wallington et al. [18] and uses them to sample data from the results shown in Fig. 1 above.

Due to X2's short test times, the displacement of free-flying models tested in X2 is often in the order of a pixel between the start and end of the test time. For accurate force measurement, sub-pixel accuracy is required when determining the position of the model. The model's position is determined by the workflow shown in Fig. 2.

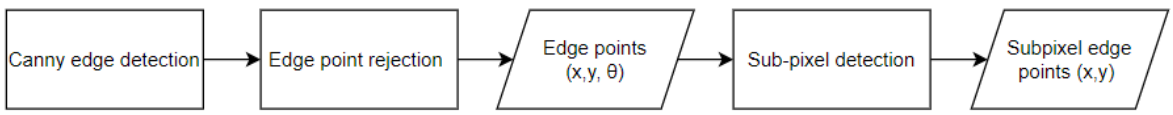


Fig 2. Sub-pixel edge detection workflow

Firstly, Canny edge detection is performed over the entirety of the frame. Canny edge detection is a technique for detecting edges in images with a high level of accuracy, for further details of it refer to [28]. As an artifact of stagnated flow in the facility, the Canny edge detection algorithm often includes some false edge points, which were not the physical edge of the model. These points are removed by applying a mask which rejects points that are not within a tolerance radius of the model's expected outline (as shown in Fig. 3). The model's initial outline was known from a reference frame taken before the shot. Typically, a mask of $\pm$ 2 pixels worked well for removing false edge points.

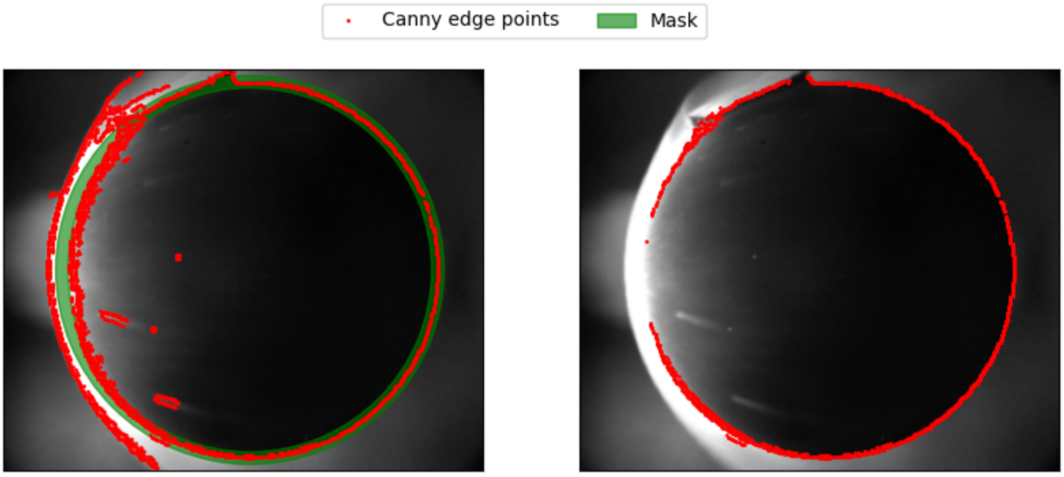
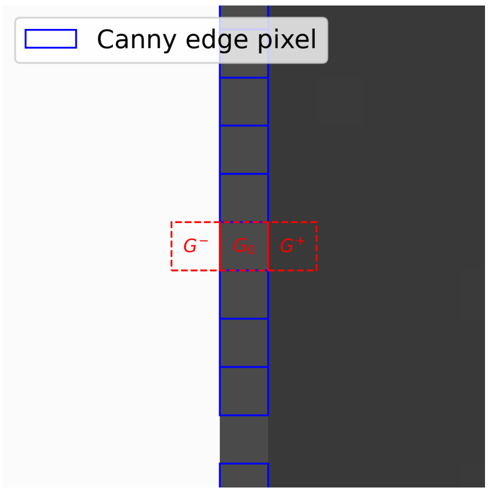


Fig 3. Canny edge points before (left) and after (right) mask is applied

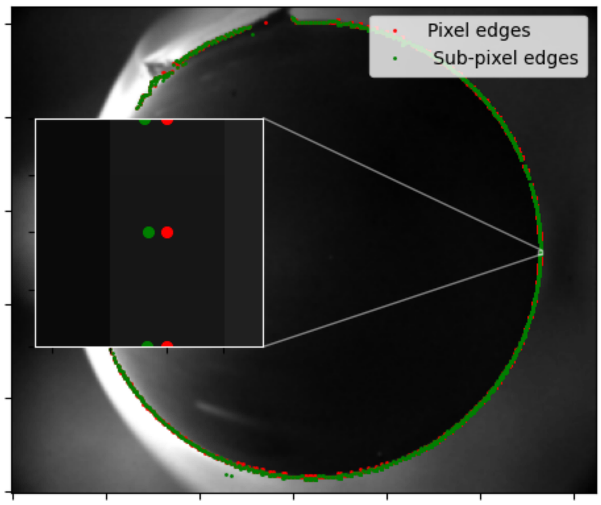
At this stage each Canny edge point has an x, y and θ. θ refers to the angle of the edge at a point. For typical, square pixels edges are either horizontal, vertical or diagonal. The sub-pixel location is determined by interpolating the gradient of brightness across the edge, notated as G^-, G_0 and G^+ (shown in Fig. 4a). For vertical and horizontal edges the sub-pixel location is approximated as:

$$d_s = 0.5 \cdot \frac{G^+ - G^-}{G^+ - 2G_0 + G^-} \tag{1}$$

Diagonal sub-pixels require more involved calculations, for which details can be found in [7]. Fig. 4b shows the difference in the edge points (at single pixel resolution) and the sub-pixel edges.



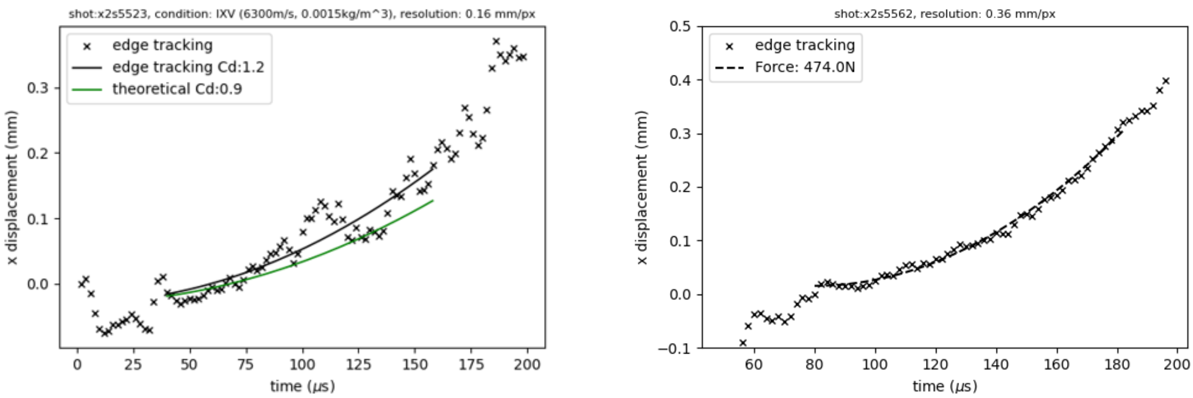
(a) Canny edge pixels and neighbouring pixels



(b) Zoomed in section of sphere model with sub-pixel edges

Fig 4. Sub-pixel resolution theory and application

Once the sub-pixel edge points have been established, the model's position throughout the test time is tracked using a least squares fitting method. A function of the model's outline (i.e. a circle function or a spline from a CAD package) is converted to a polar function $r = f(\theta)$. This polar function is transformed in the x and y direction and rotated (α) until the least squares function is minimised. The model's displacement is found by comparing x, y and α values from sequential frames. It was found that by using the 'Cauchy' fitting method from the Scipy least squares module the effect of outlying edge points was minimised. An estimate for acceleration was made by fitting a quadratic equation to the displacement values over the test time. Fig. 5 shows the x (drag) direction displacements for the sphere and Orion capsule free-flying campaigns in X2 (which have sample images shown in Fig. 1 above). In particular, the Orion capsule's displacement (Fig. 5b) has a relatively small amount of noise and shows a clear quadratic trend, which can be associated with a constant acceleration. The Sphere's displacement (Fig. 5a), while more noisy, also shows a similar trend. Y (lift) and rotational (Moment) optical tracking is yet to be achieved since they yield significantly less displacement. However, considering no Schlieren was used for these campaigns they serve as a proof of concept that motion tracking can be achieved in X2. Further campaigns with a Schlieren system will be performed for Lift and Moment measurements.



(a) Sphere x direction displacement

(b) Orion capsule x direction displacement

Fig 5. x (drag) direction displacements and fitted quadratic for Sphere and Orion capsule free-flying campaigns in X2

4. Off-axis Parabolic (OAP) Schlieren System

As part of an Honours thesis last year, a new X2 schlieren system was designed using OAP mirrors for use in future free-flying model testing on the X2 facility [27], based on a design from Zheng et al. [29]. Compared to a traditional z-type schlieren system, OAP mirrors allow a much more compact schlieren system to be designed without the addition of optical aberrations. This is important for two reasons. Practically on X2, schlieren can be performed on the facility but it often isn't, due to the difficulty of setting up a large schlieren system on a facility which is generally not used to perform schlieren measurements. Secondly, it will allow bright, narrow wavelength laser schlieren light sources to be used on X2 in the safest way possible as the laser light can be easily contained in boxes due to the compact size of the schlieren system. UQ's Centre for Hypersonics owns a Cavilux HF schlieren laser, but using it on X2, in a large open schlieren system, is not deemed to be safe or practical. With an OAP system, the schlieren system is compact enough that it can easily be fully enclosed so the schlieren laser can be used safely.

A schematic of the system can be seen in Fig. 6 below. Preliminary testing of the system was carried out on UQ's Drummond tunnel with a green LED light source instead of the schlieren laser. A Phantom v2012 ultra-high-speed camera was used to image the model during the experiment. The enclosures have been made and were used in the Drummond tunnel experiments without the side panels or interlocks installed. This year it is planned to finish the system and test it on X2 with the schlieren laser in use.

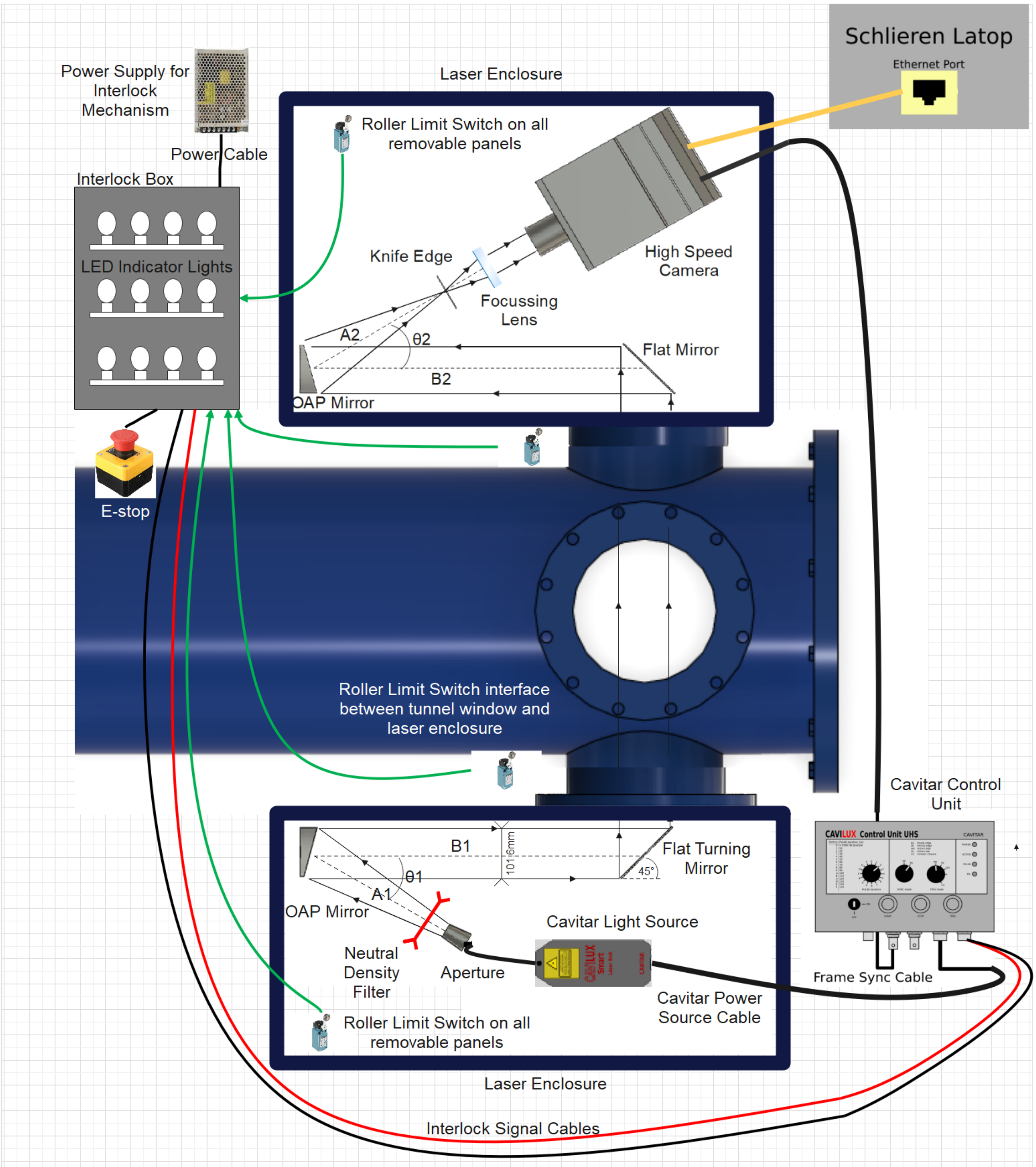
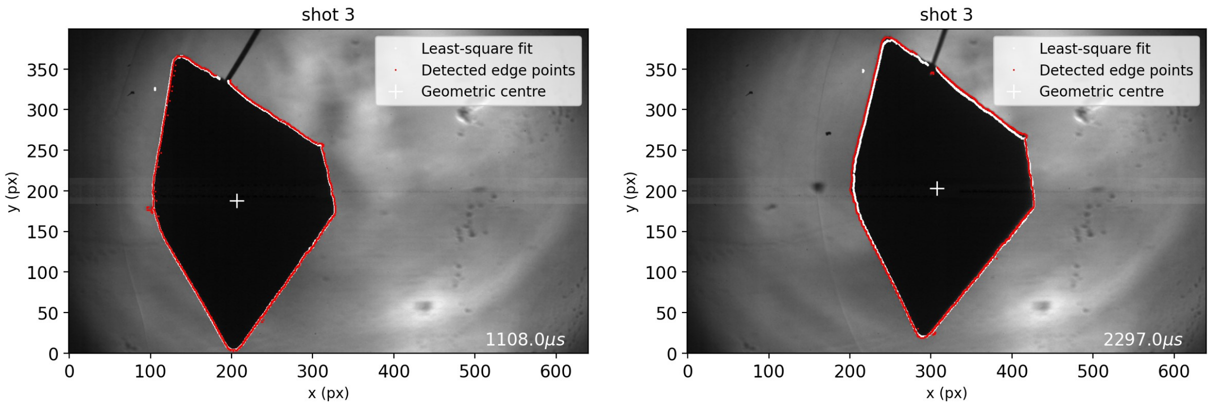


Fig 6. Schematic of the X2 OAP laser schlieren system from Bui [27].

In the Drummond tunnel experiments, both capsule and glider models were tested, with a sample result shown in Fig. 7 below. As the system was set up mainly for backlighting the model, the schliering effect is quite weak so while the bow shock is visible, it is fairly faint. What can be clearly seen in the image is that the outline of the whole model can be seen clearly and that the edge detection has found the whole model. This kind of result is very promising for when this system is applied to X2 in the future.



(a) Drummond experiment E3 Frame 82 **(b)** Drummond experiment E3 Frame 170

Fig 7. Example schlieren results using our new OAP schlieren system for a capsule model in UQ's Drummond tunnel.

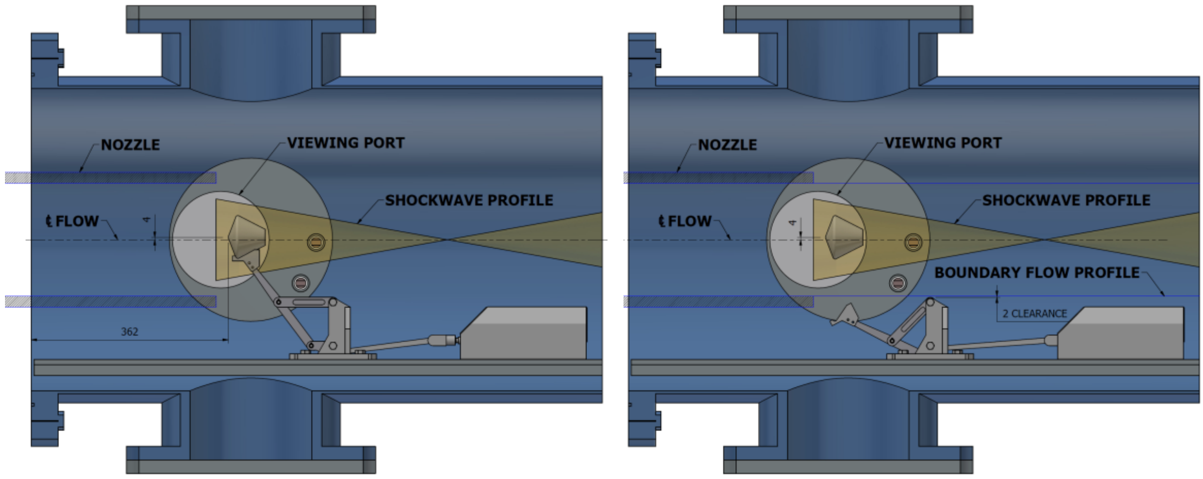
5. Model Release System

Free-flying models need to be held in place before an experiment, meaning that some kind of model suspension and/or release system is required. Generally models are held up by string or fishing line which is destroyed when the flow arrives at the model. This has been done for all previous X2 free-flying model research. More complicated systems have been used in some cases, such as the spring-based, dropping model release system used on the TUSQ hypersonic facility at the University of Southern Queensland (UniSQ) [30]. The UniSQ system is pre-tensioned and held in place by two solenoids which move out of the way when actuated, causing the model release system to quickly drop, leaving the test model in place when the test flow arrives. A Chebyshev linkage arrangement is used, which is a linkage system specifically designed to result in approximately linear displacement.

Last year a final-year engineering Major Design Project team at UQ designed a model release system for use on X2 [31], inspired by the design from [30]. It makes use of the same Chebyshev linkage as the UniSQ system except instead of using springs, it is pneumatic and runs off shop air. This was required because the UniSQ model release system moves out of the way of the flow in 70 ms, which was deemed to be too slow considering that on X2, the piston compression process, which starts the experiment and could be used to trigger the release mechanism, occurs over durations of 20 to 30 ms [32], which is far shorter than the drop time of the UniSQ system.

Our system is actuated by a solenoid valve which lets shop air into the pneumatic cylinder, pushing it back and causing it to pull on one of the linkages, which pulls the linkage holding the model down and out of the way of the test flow, leaving just the model in place to free-fly during the experiment. Two schematics of the system set up in the test section of our X2 facility can be seen in Fig. 8. The X2 nozzle, viewing window, and approximate core flow geometry can also be seen in the schematics. In Fig. 8a the system is seen in its 'up' position before the experiment, where it is holding a representative aeroshell test model. In Fig. 8b the system is seen in its 'down' position during the experimental test time, with the system out of the way of the flow and the test model free-flying in the facility core flow.

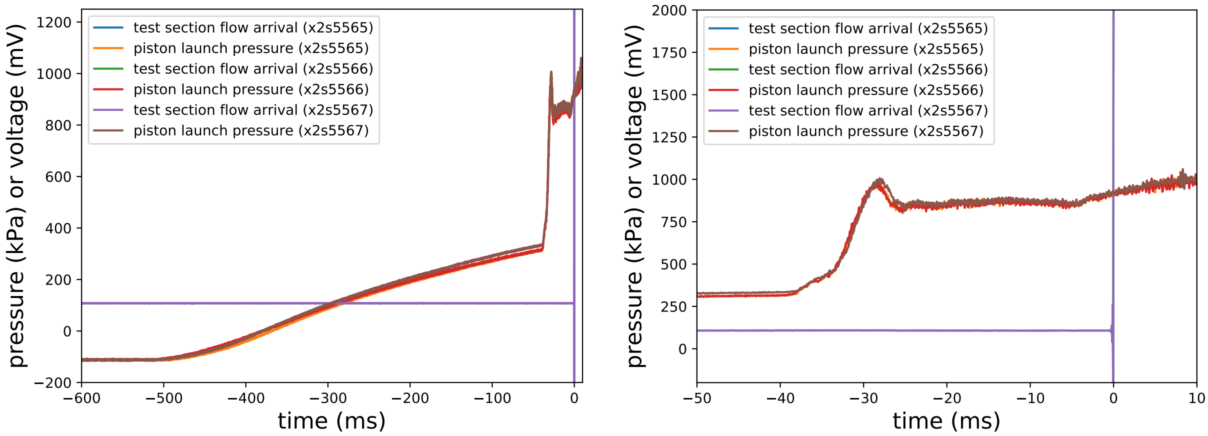
The model release system is triggered by a Kulite pressure transducer mounted in the line that fires X2's free-piston off its launcher, initiating the experiment on the facility. This was chosen instead of the facility recoil trace which is used for long duration triggering on some others facilities, such as UQ's T4 reflected shock tunnel (a recent example of this timing on T4 can be found in Trudgian et al. [33]), as we believed that this would give more time as it responds when the valve is opened but *before* the piston fires off the launcher, not after it is already moving, and we wanted the maximum amount of time for the solenoid to actuate.



(a) system up position before an experiment **(b)** system down position during the experimental test time

Fig 8. Schematics of the model release system installed in the X2 expansion tube test section [31].

Example Kulite pressure data compared to the flow arrival time in X2's test section for three different consecutive X2 experiments performed with the same driver condition can be seen in Fig. 9 below. Flow arrival in X2's test section is marked as 0 ms on the plot. Fig. 9a shows the pressure over a long time scale of more than 500 ms which appears to show X2's fire valve opening and potentially the cavity filling which pushes the piston off the launcher. This opening time appears to be very repeatable, even though the valve is opened manually. A shorter duration plot focused on the spike in signal and later higher pressure region seen around -38 ms is shown in Fig. 9b.



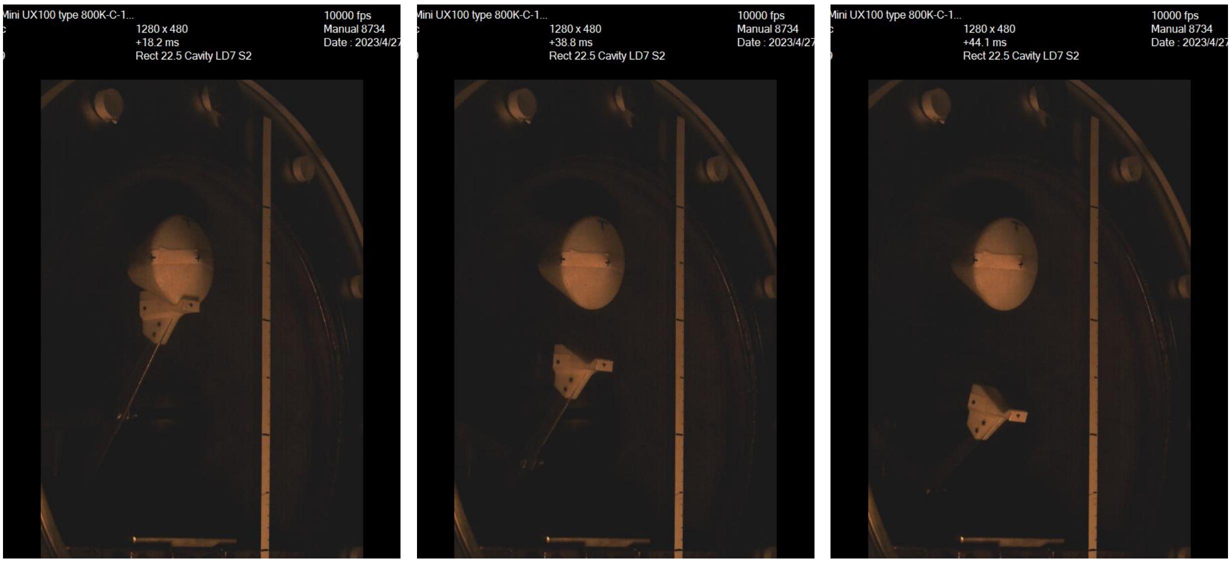
(a) long time duration showing valve opening time **(b)** short time duration showing piston launch

Fig 9. Pressure in the cavity fill line which fires the X2 facility compared to flow arrival time in the X2 test section for three consecutive experiments using same X2 driver condition.

It can be seen in Fig. 9b that the Kulite pressure starts to rise sharply around 38 ms before test section flow arrival. This spike is sharp making it a good candidate for triggering the model release system. In this case, 38 ms would be the maximum time required for the model release system to push the model mount out of the way before the flow arrives, allowing the model to experience undisturbed, free-flying flow in the facility. It can also be seen that the cavity behaviour and timing are very repeatable between experiments, giving confidence that the system can be synchronised with the facility firing. It should be noted that this condition only has a compression ratio of 20 and that other X2 driver conditions, with higher compression ratios of 30 and 40, will compress faster [32], which will be more challenging for the system. Another option would be to try to trigger off the gradual rise starting at 500 ms before flow arrival which is shown in Fig. 9a. This would give ample time for the model release system to operate, as long as a control system could tell it to open its solenoid at the correct time to synchronise with flow arrival in the test section. The system already has a control system implemented for this purpose so this should be relatively simple if it is required.

Preliminary testing of the system has been performed under atmospheric conditions in a vacuum chamber in our laboratory, with an example result from a high-speed camera shown in Fig. 10 below. In Fig. 10a it can be seen that at 18.2 ms after the trigger the model mount starts to move. Around 38 ms after the trigger (Fig. 10b, when the flow is predicted to arrive, the mount is retracted but not fully. It takes until 44 ms after the trigger for the mount to be fully retracted (Fig. 10c).

The result shown in Fig. 10 above is very promising for a first try, as it is within 6 ms of the required timing. Work is continuing to try to close this gap, such as the design of lighter links which are to be tested in the coming months. Another option is to trigger off the fire valve opening shown in Fig. 9a, which will provide around 500 ms before flow arrival for the system to operate, which may end up being the better option. Further testing needs to be performed to verify that the system will behave similarly under vacuum and that it will not leak and compromise the pressure in the dump tank of the facility when it is actuated before the experiment. Finally, testing will need to be done outside the X2 dump tank to test that it can be synchronised with an X2 experiment, with the system outside of the test section, and then it will be used for a proper X2 experiment.



(a) 18.2 ms after trigger **(b)** 38.8 ms after trigger **(c)** 44.1 ms after trigger

Fig 10. Example atmospheric pressure drop test of the model release system.

6. Future Opportunities

UQ's X2 expansion tube is one of the highest-performance impulse wind tunnels in the whole world, which is able to simulate entry into all of the planetary bodies in the solar system, as well as high-speed flight in the Earth's atmosphere. As this paper has shown, once all of the pieces discussed in this paper, sub-pixel resolution optical tracking, schlieren to backlight test models, and the model release system, are ready, X2 will be able to measure the forces experienced over blunt planetary entry vehicles at the real high enthalpy conditions that these vehicles experience in flight. This is very important, as while a lot of re-entry capsule force measurements have been performed in reflected shock tunnels, such as in Laurence et al. [1, 5], these measurements were performed at enthalpies far lower than peak heating in flight, meaning they are not able to assess the effect of the flow chemistry seen near peak heating on the forces to these vehicles - free piston driven expansion tubes, like X2, are the only impulse facilities which can do this. This is what we plan to start investigating in future work.

Another opportunity for free-piston driven expansion tubes like X2 is to use their high-performance free-piston driver to study very high total pressure conditions flying through the atmosphere, instead of re-entry conditions. This is where Bui's free-flying glider project came from [27]: we wanted to show that X2 could measure the forces experienced by boost-glide vehicles such as the HTV-2 [34, 35] which glide through the atmosphere starting at speeds of over $6\,\mathrm{km/s}$. While we are still unsure whether the HTV-2 could be tested in X2 due to X2's short test times, other vehicles like it, may be able to be studied in X2, and this is also something which we plan to continue to investigate.

While X2 has been used to measure the displacement of lightweight models to measure forces in many projects (discussed in Section 2 of this paper), a current honours thesis project is exploring the flow chemistry of free-flying aluminium sphere-cone capsules of varying geometry, shown in Fig. 11. Given the short test times of X2, heavier metal models restrict any horizontal movement, but they provide a highly-precise and realistic flow-field to better analyse an applied shock, without the effect that the model's sting may have on the flow. Consequently, these models provide an ideal foundation for the investigation of specific flow characteristics at the forebody and afterbody of the model, introducing a range of potential topics which can be investigated in the future.

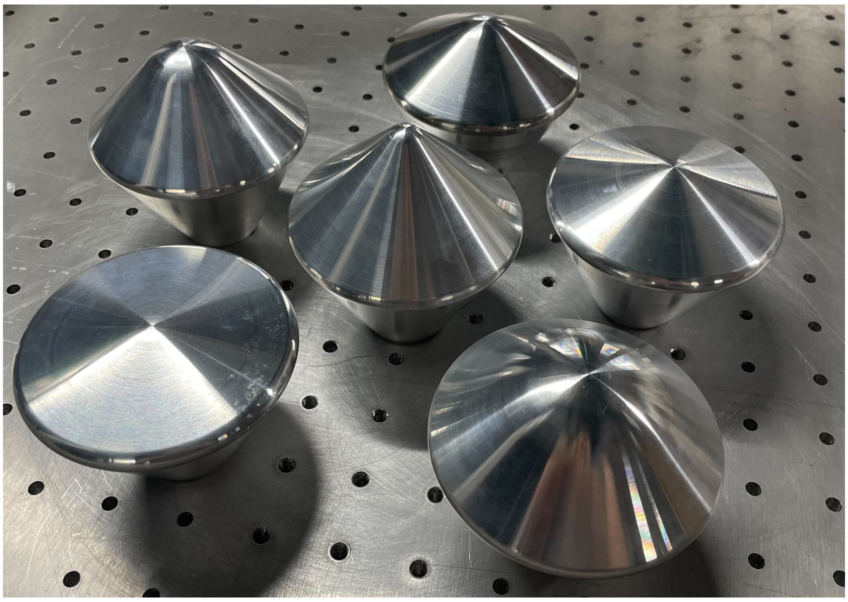


Fig 11. Aluminium sphere-cone capsule prototypes.

A recent two-part study authored by Hornung, Martinez Schramm and Hannemann [36, 37] tested similar models suspended by string in the High-Enthalpy Shock Tunnel Göttingen (HEG), which is the reflected-shock tunnel at the German Aerospace Centre (DLR), to steady the effect of post-shock vibrational relaxation on the shock standoff and forces to the models which also have varying geometry. Replicating these tests in X2, which is capable of operating at a much higher enthalpy than the HEG, meaning we can perform experiments in a dissociated flow, instead of just a vibrationally excited one, means we can produce higher enthalpy experimental results to relate nose geometry and shock standoff distance. Ground-based data in this area, which accurately reflects Earth re-entry conditions, is nonexistent thus far. This gap provides a meaningful opportunity for X2 testing.

The project also allows the aforementioned schlieren and model release systems (Sections 4 and 5) to be implemented on X2 and improved, including the adaptation of the free-flying release mechanism under greater loads. Advancing the method of free-flight during these tests is an additional way in which UQ can build on the results from the HEG tests. Through the development of this thesis, future opportunities are introduced for both free-flight experiments in X2 using models of various materials, and the detailed flow analysis of sphere-cone capsule geometries. This work can assist in UQ's contribution to re-entry vehicle optimisation through shock measurement, utilising its advanced facilities to justify relevant computational findings which are yet to be verified experimentally.

7. Conclusions

Overall, this paper has highlighted the development of free-flight model testing on UQ's X2 expansion tube through a series of different projects over the last 5 years. We have shown that if models are light enough and blunt enough, free-flight model force testing can be performed in X2, even with our severely limited 100 µs test time. We have developed sub-pixel resolution optical tracking techniques, a schlieren system to visualise models, and a model release system to allow us to test models without needing to use string to hold them up. Using these developments, we plan to continue this testing on X2 to allow us to study the forces experienced by planetary entry vehicles at peak heating, which only free-piston driven expansion tubes can do, vehicles flying at high-speed in the Earth's atmosphere, and the flow around capsules without the interaction of a sting mount using heavy free-flying models.

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