18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

Vibration Isolation in a Free-Piston Driven Expansion Tube

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Abstract

The stress waves produced by rapid piston deceleration are a fundamental feature of free-piston driven expansion tubes, and wave propagation has to be considered in the design process. For lower enthalpy test conditions, these waves can traverse the tube ahead of critical flow processes, severely interfering with static pressure measurements of the passing flow. This paper details a new device which decouples the driven tube from the free-piston driver, and thus prevents transmission of stress waves. Following successful incorporation of the concept in the smaller X2 facility, it has now been applied to the larger X3 facility, and results for both facilities are presented.

Introduction

The expansion tube class of hypersonic flow facility is uniquely capable of producing short duration test flows up to 15 km/s, at gigapascal total pressures. The University of Queensland (UQ) has two expansion tube facilities; X2 has a total length of 23 m and was originally commissioned in 1995; X3 is much longer at 69 m, and was commissioned in 2001. Both facilities are powered by free-piston drivers, which provide the total pressure capability necessary to produce test flows ranging from super-orbital planetary entry conditions (6-15 km/s), to high Mach number scramjet access-to-space conditions (3-5 km/s).

A schematic of the X2 facility is shown in Figure 1 and is used to explain the operation of both UQ facilities. A massive piston is accelerated along the compression tube by high pressure reservoir air, attaining a high velocity, and compressing helium driver gas ahead of it (possibly mixed with argon). The driver gas is initially separated from the downstream driven tube by a steel diaphragm, scored so that it ruptures in a clean and repeatable fashion. Towards the end of the piston stroke the driver gas pressure is sufficient to rupture the diaphragm, initiating a shock in the driven tube and the subsequent downstream flow processes. Simultaneously, this high driver pressure applies a large magnitude impulsive axial load to the tube.

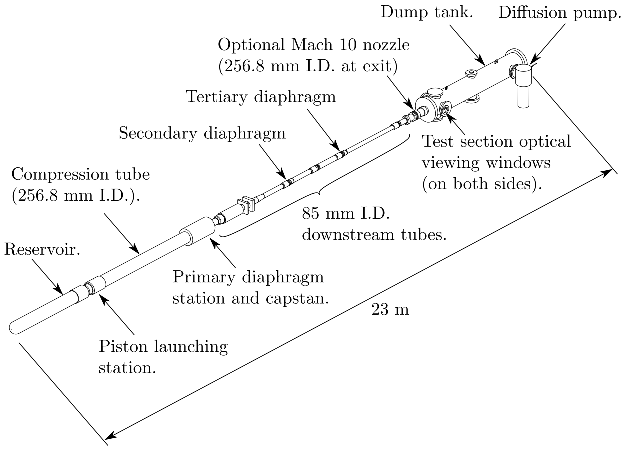


Figure 1: Schematic of X2 expansion tube facility, shown to scale, with nozzle attached.

Secondary and tertiary light Mylar diaphragms are used to initially separate downstream tube sections which may contain different gases at different pressures. In basic expansion tube mode the test gas is contained between the steel primary diaphragm and a Mylar secondary diaphragm. A low pressure gas fills the remaining downstream acceleration tube and dumptank, which includes the test section. The primary shock first processes the test gas. The shock ruptures the secondary diaphragm upon its arrival, allowing the shock processed test gas to expand into the low pressure acceleration tube. The test gas undergoes an unsteady expansion along the length of the acceleration tube, gaining significant total enthalpy, before eventually passing over the model in the test section and providing the flow experiment.

Many high enthalpy conditions as well as scramjet conditions benefit from operation of the expansion tube with a shock-heated secondary driver [4]. This is a volume of helium contained at the beginning of the driven tube, between the primary diaphragm and the test gas, and requires the use of a second thin Mylar diaphragm. The secondary driver provides additional shock strength for high enthalpy conditions, but is also used for relatively low enthalpy scramjet conditions to prevent corruption of the test flow by acoustic disturbances originating in the free-piston driver (a noise mechanism originally identified by Paull and Stalker [5]).

UQ's X2 and X3 free-piston driven expansion tube facilities are routinely used to produce super-orbital test flows, such as planetary entry between 6 and 15 km/s. At these speeds, the average shock speed down the tube typically exceeds the speed of sound in steel, and the flow measurements of interest complete before the arrival of mechanical stress waves from the free-piston driver. However, by virtue of their immense total pressure capability, these facilities are increasingly being utilised to simulate scramjet access-to-space flow conditions. Scramjet flow conditions typically entail average shock speeds through the driven tube of approximately 2-3 km/s. Stress waves originating at the driver, which travel down the steel tube at approximately 5 km/s, will overtake the shock wave in these conditions. This can present a particular problem in the acceleration tube, where relatively high sensitivity pressure transducers are used since pressures are low.

X2 and X3 use PCB sensors to make these pressure measurements. The PCB sensor comprises a stiff but deformable steel diaphragm attached to an internal piezoelectric sensor crystal which produces a charge when it is stressed [1]. The diaphragm displaces under pressure loading, and a correlation between deflection and charge can be used to measure pressure. However, when a PCB is subject to large accelerations, the diaphragm may also displace relative to the crystal due to inertial effects. In such cases an erroneous pressure measurement may be made. The sensitive PCBs used for the acceleration tube have correspondingly more flexible diaphragms, and therefore are particularly sensitive to forced accelerations of the sensor.

Following attempts to simulate scramjet flow conditions in X2, unacceptably noisy static pressure traces were measured in the acceleration tube. Figure 2 shows examples of three static pressure traces for a Mach 12.5 flow condition. Transducers ‘at4’, ‘at5’, and ‘n1’ are respectively located at 1.6, 1.9, and 2.7 m downstream of the tertiary diaphragm (refer Figure 1). It can be seen that large amplitude noise begins prior to the arrival of the primary shock, which would normally be evidenced by a sudden rise in static pressure as the shock passes the transducer. The actual test flow static pressure is almost entirely obscured by the noise, and very little useful information can be inferred from these traces. This is problematic, since knowledge of the true static pressure through the acceleration tube, particularly near the tube exit, helps to characterise the test gas immediately prior to its arrival in the test section or nozzle inlet.

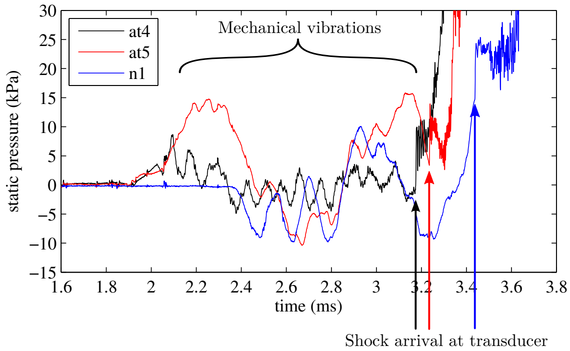


Figure 2: Acceleration tube static pressure transducer responses for Mach 12.5 flow condition x2-scr-m12p5-rev-1 from [2].

It was considered highly likely that the noise in Figure 2 was due to mechanical disturbances from the free-piston driver, and it was postulated that introducing compliance at one of the upstream tube joins might reduce transmission of stress waves to the acceleration tube. A new design concept was therefore proposed which would axially decouple X2’s driven tube at the secondary diaphragm station tube connection.

A New Secondary Diaphragm Holder/Buffer for X2

In X2’s previous configuration, the thin Mylar secondary diaphragm was held in place by clamping it between the upstream and downstream tubes, simultaneously forming a rigid connection between the tubes. In this arrangement, mechanical disturbances in the upstream tube are transmitted directly into the downstream tube, like those evident in Figure 2.

Mechanical disturbances are associated with a rapid finite displacement vs. time profile of the upstream tube at the tube interface, which depends on the mass and geometric properties of the attached downstream tube. It would be expected that this displacement would be a maximum if the downstream tube was fully disconnected from the upstream tube. Although this is impractical, there would be no transfer of the mechanical disturbance. However, the magnitude of the force transferred to the downstream tube can be reduced significantly if a section of compliant material is located between the two tubes.

A new secondary diaphragm holder/buffer device was developed for X2. Figure 3 shows a schematic of the device. Here the new arrangement locates the Mylar diaphragm in an independent cartridge unit, and removes the requirement for a stiff clamping arrangement between the tubes. The upstream rubber bumper is a 6 mm thick ring of rubber which acts as a relatively soft interface between the tubes. There is sufficient diametric clearance in the cavity containing this ring to permit approximately 3 mm compressive displacement before the volume is fully blocked by the deformed rubber. Finally, o-rings ‘1’ and ‘4’ in Figure 3(a) permit axial movement of the tube whilst maintaining a vacuum seal. Since supporting the diaphragm and sealing the tube no longer depend on a large compressive axial force at the tube join, the secondary diaphragm station can now be assembled with minimal clamping force, and once assembled permits a small degree of relative tube movement without significant load transfer between tubes.

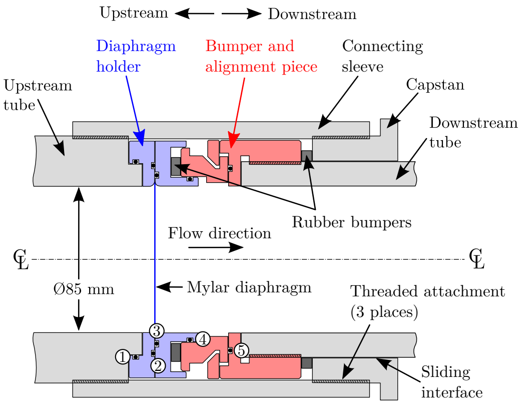


Figure 3: Schematic of X2 diaphragm buffer/holder assembly.

The compliant rubber buffer material must be sized to accommodate deflections characteristic of the specific free-piston driver configuration. There are two characteristic deflections of the tube during operation of the free-piston driver. The entire tube is supported by roller bearings, and is free to move axially. Since the piston moves forward during an experiment, conservation of momentum requires that the facility correspondingly recoil in the opposite direction. Loading of the downstream tube cannot be avoided since it eventually must recoil with the upstream tube in this particular setup. However, this recoil action occurs over relatively long time scales and is not thought to induce accelerations in the tube wall of sufficient magnitude to interfere with tube wall static pressure measurements to the extent evident in Figure 2. In addition to the fundamental recoil motion of the facility, there is additional transient loading of the tube, primarily due to the large impulsive load applied to the compression tube by the decelerating piston. This loading can produce strong longitudinal stress waves, and is thought to be the primary source of the observed mechanical disturbances.

While the characteristic magnitude of these deflections was not determined prior to designing this new device, reference was made to tube recoil data which is routinely recorded during experiments. Using X2’s recently commissioned tuned lightweight free-piston driver [3], the tube recoil has been measured experimentally to be between 4 and 5 mm, which occurs steadily over approximately 20 ms. In comparison to this total tunnel recoil, transient displacements at the secondary diaphragm due to piston impulse loading would be expected to less, thereby probably making the 3 mm of travel incorporated into the new design sufficient.

Referring to Figure 3, there is an additional rubber bumper located downstream of the secondary diaphragm. This is also designed to act as a compliant buffer against axial loading due to recoil motion of the tube. While this buffer cannot accomodate the entire tube recoil motion, it has sufficient travel to accomodate higher speed but lower magnitude deflections.

Results with X2

Figure 4 shows an example of experimentally measured acceleration tube wall static pressure traces when the new diaphragm holder/buffer assembly is installed. These results are for the same Mach 12.5 flow condition considered in Figure 2. It can be seen that the mechanical disturbances identified in Figure 2 are practically eliminated, and the arrival of the shock at each transducer is now evident.

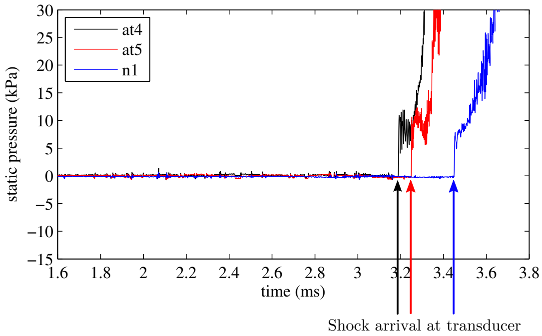


Figure 4: Acceleration tube transducer responses for Mach 12.5 flow condition x2-scr-m12p5-rev-1 [2], *after* installation of new diaphragm holder and buffer arrangement (see Figure 3).

In addition to improving the quality of the recorded pressure traces, containing the diaphragm in a separate cartridge unit ensures that the thin diaphragm is seated properly and fully supported; this, in turn, improves the quality of the vacuum seal obtained across the diaphragm, and improves the operational reliability. These two benefits alone justify the additional shot-by-shot turnover effort associated with the new design.

The X3 Expansion Tube

The X3 expansion tube is the larger of UQ's two expansion tubes. With a length of approximately 69 m and an acceleration tube bore diameter of Ø182.6 mm (compared to 23 m length and Ø85.0 mm bore for X2), X3 can achieve equivalent flow conditions to X2, but can accommodate much larger models and provide much longer duration test times. In recent years X3 has undergone several upgrades, including the development of a new single-stage free-piston driver, modification to incorporate a contoured Mach 10 nozzle, a new test section and dumptank, improved instrumentation and data acquisition, and various other upgrades. At the time of writing a number of shots have been successfully performed with the upgraded facility. The focus of current commissioning and flow condition development has been new scramjet test conditions in support of the SCRAMSPACE project. Steady Mach 10 test flows using the new nozzle have already been achieved, with total pressure and test time exceeding 100 MPa and 1 ms respectively.

For X3, as with X2, it is very important to obtain reliable and high quality static pressure measurements of the test flow through the acceleration tube. For these new scramjet flow conditions, similar mechanical disturbances have been observed in the pressure traces through the acceleration tube of X3. Given the success of the new diaphragm holder/buffer assembly in X2, a similar concept was adapted to X3.

In X3's previous configuration, diaphragms were clamped between adjacent tube sections, and sealed by o-rings located at each tube face. For a facility of X3's size, any minor misalignment of two adjacent tube faces can result in uneven clamping force on the diaphragm, resulting in leaks and even slippage of the diaphragm under pressure. Additionally, the diaphragm can become unseated during assembly of the two massive tube sections, and subsequent problems may only become apparent once the facility has been fully assembled and pumped down.

Figure 5 shows new cartridge diaphragm holders developed for both the secondary and tertiary diaphragm stations of X3. These hold the diaphragm securely in place during turnover of the facility, and significantly improve the reliability of the diaphragms. Neither leakage across the diaphragm, nor slippage and/or damage to the diaphragm during turnover, nor gas filling of the tubes, have occurred since incorporation of these new components.

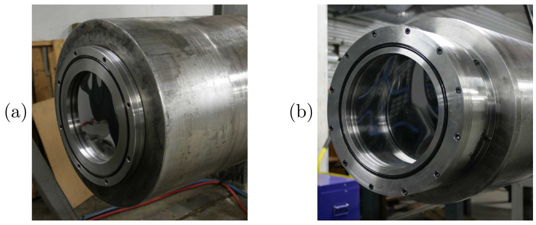


Figure 5: (a) Secondary diaphragm holder; (b) Tertiary diaphragm holder and mechanical buffer assembly.

Referring to Figure 5(b), the tertiary diaphragm station was also modified to incorporate a buffer against upstream mechanical disturbances. The design of the new buffer is detailed in Figure 6. A sliding o-ring seal is still retained in the buffer mechanism (o-ring '6' in Figure 6), however unlike with X2, axial compression is required to seal the o-rings against the upstream tube (o-rings '1' and '2' in Figure 6). This arrangement was necessary due to the different initial configuration of X3's tertiary diaphragm station compared to X2.

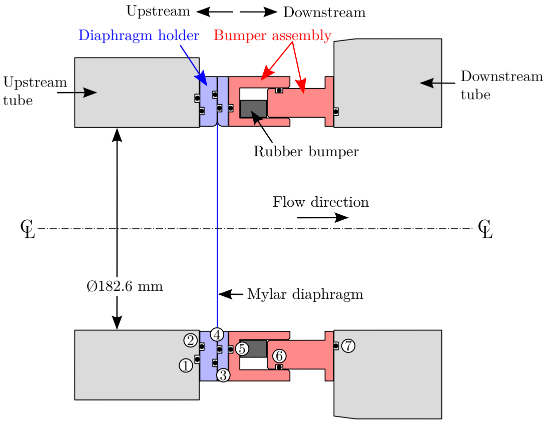


Figure 6: New X3 diaphragm buffer/holder assembly; the tube connecting sleeve and capstan nut are not shown.

The X3 arrangement also does not have a rubber buffer to accomodate recoil deflections from the driver (i.e. the compressed downstream rubber buffer in Figure 3(b) for X2). Figure 7 shows the capstan arrangement for X3's tertiary diaphragm station. Referring to Figure 7(a), recoil is transmitted through a nylon spacer. While nylon is more compliant than steel, it is nevertheless much stiffer than rubber and its ability to buffer recoil disturbances may be correspondingly poorer.

The performance of X3's new diaphragm buffer/holder assembly has been assessed during the development of new Mach 10 flow conditions for the SCRAMSPACE project. The buffer was initially assembled with *no* rubber, thereby ensuring a rigid tube connection across the diaphragm station. Figure 8(a) shows acceleration tube wall static pressure traces for X3 with this rigid tube connection. Shock arrival is evident in the traces, however significant mechanical noise is also evident prior to arrival of the shock. While this noise is not as severe as that observed for the X2 Mach 12.5 condition (Figure 2), it remains significant.

Figure 8(b) shows acceleration tube wall static pressure traces for another Mach 10 X3 flow condition. The only difference between flow conditions in Figures 8(a) and (b) was that reservoir

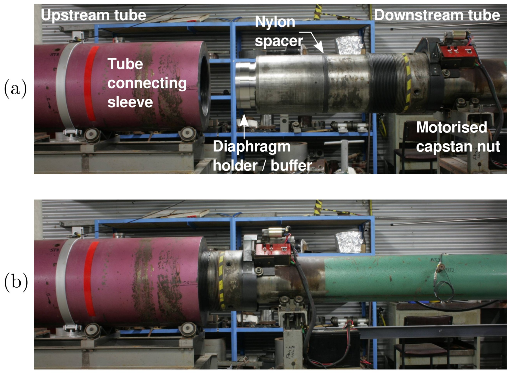
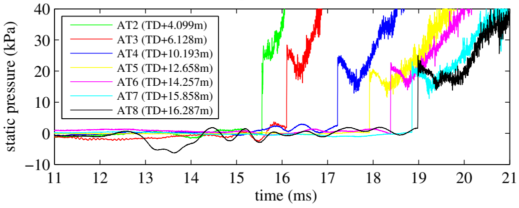


Figure 7: X3 tertiary diaphragm arrangement. (a) diaphragm station open; (b) diaphragm station closed.

pressure behind the piston was increased from 3.2 to 3.4 MPa (i.e. the piston was pushed slightly harder in Figure 8(b)); all other tunnel configuration parameters were the same. In Figure 8(b), X3's diaphragm buffer was loaded with four rubber rings with 24 mm total thickness. It can be seen that the rubber buffer has substantially removed mechanical noise from the static pressure traces, validating the design for X3.

(a) Without diaphragm buffer (shot x3s400)



(a) With diaphragm buffer (shot x3s401)

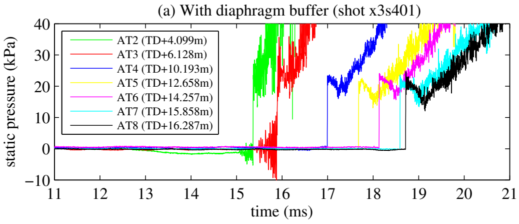


Figure 8: Acceleration tube transducer responses for a Mach 10 flow condition in X3, (a) *before* and (b) *after* installation of a new diaphragm holder and buffer arrangement (see Figures 5 to 7). Transducer locations are all located downstream from the tertiary diaphragm (TD) plane, by an amount TD+x as shown.

Interestingly, it can be seen in Figure 8(b) that use of the rubber buffer introduces high frequency mechanical noise to the AT2 and AT3 pressure traces *prior* to shock arrival. The cause of this noise has not yet been identified, however it is thought that it may be due to the transient response of the diaphragm holder within the holder/buffer assembly; the holder is impacted by mechanical stress waves from the upstream tube, and is also loaded by the normal shock wave (which causes the diaphragm rupture). It is possible that the holder temporarily 'rattles' around inside the holder cavity. The high frequency noise is only observed in AT2 and AT3, and is not apparent in transducers located further downstream. X3's acceleration tube is constructed from a number of tube sections connected by threaded sleeves. AT3 is located in a tube segment, whereas AT2 is located in a heavier cross-section connecting sleeve; the reduced noise in AT2 may be due to the heavier cross-section of the sleeve. Transducers further downstream do not exhibit this noise, possibly because the high frequency noise does not significantly transmit across the subsequent tube connections.

Initial experience with X3's diaphragm holder/buffer assembly indicates that it works most effectively when assembled with minimum pre-load to the rubber, although sufficient pre-load must be applied to compress o-rings '1' and '2' in Figure 6. Adopting a parallel o-ring seal at this interface (such as o-ring '1' in Figure 3 for X2) would remove this requirement and likely improve the operation of the buffer.

The maximum compression of the diaphragm/holder buffer during operation of X3 was measured using deformable solder rods glued between the upstream and downstream parts of the diaphragm holder/buffer. When the buffer is compressed, the deflected upstream face presents an irresistible deflection to the solder rods, therefore any contact is observed later as deflection/detachment of the rods. It was found that initial tightening of the diaphragm station compressed the buffer between 1 and 2 mm; after firing X3 at a Mach 10 condition similar to those considered in Figure 8, the maximum *total* displacement was later measured to be between 4 and 5 mm, indicating that the displacement during actual firing of the facility was approximately $(5-2)=3$ mm. This displacement is comprised of movement of the upstream tube and/or independent movement of the diaphragm holder. It nevertheless establishes a characteristic maximum deflection during operation. Considering the relative size of X2 compared to X3, the selection of 3 mm travel for X2's buffer appears to have been conservative.

Conclusions

New designs for X2 and X3 introduce devices at the secondary and tertiary diaphragm stations, respectively, which mechanically decouple the tubes at these locations. A compliant buffer separates the tubes, and a small amount of relative movement of the tube faces is permitted, thereby preventing transmission of mechanical noise from the upstream free-piston driver. The result is dramatically reduced signal noise. It has been found that the X2 design is better, since it does not require pre-loading of the diaphragm station to maintain vacuum seal. Improved operation of the X3 apparatus is still being established.

Acknowledgements

The authors wish to thank: Mr B. Loughrey and Mr F. De Beurs for technical support; The Australian Research Council and The Queensland Smart State Research Facilities Fund 2005 for support and funding; The Australian Space Research Program and UQ for their funding in support of the SCRAMSPACE project

References

[1] PCB technical information, downloaded 1 Feb 2012. http://www.pcb.com/techsupport/tech_pres.php .

[2] Gildfind, D.E., *Development of High Total Pressure Scramjet Flow Conditions using the X2 Expansion Tube*, PhD thesis, Department of Mechanical and Mining Engingeering, The University of Queensland, 2012.

[3] Gildfind, D.E., Morgan, R., McGilvray, M., Jacobs, P., Stalker, R., and Eichmann., T., Free-Piston Driver Optimisation for Simulation of High Mach Number Scramjet Flow Conditions, *Shock Waves*, **21**, 2011, 559–572.

[4] R.G. Morgan, R.J. Stalker, Double Diaphragm Driven Free Piston Expansion Tube, 18th International Symposium on Shock Waves, Jul 21-26, Sendai, Japan, 1991.

[5] A. Paull, R.J. Stalker, Test flow disturbances in an expansion tube, *J. Fluid Mech.*, 1992, **245**, 1992, 493–521.