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Design of water shock tube for testing shell materials

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Abstract

This paper presents design considerations for a shock tube experimental rig used to investigate the dynamic failure mechanisms of shell geometries subjected to water shock impact loading. In such setup, it is desirable that the drive pressure used within the tube can provide a wide range of impulsive loads on the test structures and some flexibility can be achieved on the applied pulse durations. With this aim a review of various existing shock tube experimental setup is presented and choices are made based on scientific merits. Finally design parameters are drawn for right set of conditions required for the experiments.

Key words: *water shock wave, shock tube, water shock impact, dynamic loading, shell structures*

1. Introduction

Violent disturbances such as result from the detonation of explosives, from the flow through rocket nozzles, from supersonic flight of projectiles, or from impact on solids – differ greatly from 'linear' phenomena involving sound, light or electromagnetic signals. Due to the temperature limitations of conventional methods for obtaining aerodynamic information, such as supersonic wind tunnels, it became necessary to devise new methods for simulating high Mach number and high enthalpy (high stagnation temperature) flows. The shock tunnel is one method which can, for short time duration, simulate high free flight Mach numbers and stagnation temperatures. One of the basic components of a shock tunnel is a shock tube.

The shock tube is a device in which a normal shock wave is produced by the sudden bursting of a diaphragm separating a gas at high pressure from one at lower pressure. The simplest form of a shock tube is where the high pressure and low pressure sections are commonly referred to, respectively, as the driver and driven sections of the tube. When the diaphragm bursts a shock wave forms almost instantaneously and propagates into the driven section, while simultaneously an expansion wave propagates, in the opposite direction, into the driver section. The propagation of the shock front and expansion fan changes the gas pressure, temperature, and density, and sets the gas in motion relative to the shock tube walls. The strength of the shock wave and expansion fan thus produced depends on the initial pressure ratio across the diaphragm and on the physical

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properties of the gases in the driver and the driven sections.

It is found that there is a gap in understanding the failure of shell structures under dynamic water shock loads and their interaction. Although some work on transient pressure loading and failure of curved structures has been undertaken (Schokker *et al*., 1996; Gupta and Easwara Prasad, 1999; Syrunin and Fedorenko 2006), however these have been limited to specific test scenarios. Work has been carried out on plates and regular shaped shells and include cylindrical shells subjected to external pressure loading with application to marine/submarine structures (Schokker *et al*., 1996), the effect of an explosion inside the shell (Syrunin and Fedorenko 2006). The effect of low velocity impact upon structures has also been studied extensively in the past decade (Tsai and Wu, 1971; Hawyes *et al*., 2001; Abrate 2005). All of the above investigations focused on flat plates while most structures in the industry are composed of shells or curved panels.

The objectives of this research work is to design a shock tube to examine the dynamic failure mechanisms of shell structures subjected to water shock impact loading.

2. Shock tubes working principle

A literature survey was carried out to understand that how different types of shock tubes work as discussed below.

2.1. Diaphragm shock tube

Shock tubes with a bursting diaphragm are the most commonly used shock tube type. The test being conducted begins with the bursting of the diaphragm. There are three common methods used to burst the diaphragm:

(1) A plunger with a bladed cutting edge on the end can be built into the driver tube; actuating the plunger (electrically, hydraulically, or pneumatically) drives the blade through the diaphragm material to burst it. However, this requires a somewhat complex mechanism.

(2) Another method is to use diaphragms (such as aluminium discs) that have been scored in a cross-shaped pattern to a calibrated depth, designed to rupture when the pressure difference across the diaphragm is the difference specified for the test being conducted.

(3) A third method is to use a combustible mixture of gases in the driver; initiating combustion creates a sudden increase in pressure that bursts the diaphragm (shock tubes of this design are said to use a combustion driver).

2.2. Non-diaphragm shock tube

A non-diaphragm type shock tube has been developed for the gas-dynamic laser research (Kugimiya *et al*., 2004). In the non-diaphragm type shock tube, there is no necessity for replacing a diaphragm after each experiment. Thus, it is possible to reduce influx of impurities in the experiment. In addition, the reproducibility and the efficiency of experiments may be expected to be largely improved. In this tube a valve is used instead of a diaphragm to control the pressure of the driver gas.

2.3. Liquid shock tube

New techniques using high-pressure liquid shock waves are currently being explored and are showing potential not only as a production technique but also as a versatile and controllable experimental laboratory facility for studies in metal deformation and fracture, at intermediate to high strain rates. The deformation of metal plates and tubes achievable through the use of liquid shock waves generated in a shock tube with reference to both free-forming and forming the metal into dies, as well as to imprinting detailed features. The process is highly controllable, in terms of the magnitude and duration of the applied pressure pulse (Skews *et al*., 2004).

2.4. Others

Shock tube with changes in the cross-sectional area are said to have positive or negative chambrage if the cross-sectional area of the driver section is larger or smaller than that of the driven section respectively. The primary motivation for considering shock tubes with positive chambrage is to increase the shock strength (Haselbacher *et al*., 2007).

Open-ended shock tubes have been used in many experimental studies of the discharge of weak or strong shock waves from ducts. For example, (Yu and Grönig, 1996) have studied the propagation processes of three open ended tube exits, the simple tube exit, a tube exit with ring and a coaxial tube exit, and a new method was developed to improve the shock wave technique for cleaning deposits on the surfaces in industrial equipment, by changing the tube exit geometry to decrease the attenuation of a shock wave emerging from an open-ended shock tube exit into a large free space.

U-bends tube was used to study the experimental and computational data on initiation, propagation, and stability of gaseous fuel–air detonations, for the design optimization of pulse detonation engines (Frolov *et al*., 2007). The experimental results with the U-bends of two curvatures indicate that, on the one hand, the U-bend of the tube promotes the shock-induced detonation initiation. On the other hand, the detonation wave propagating through the U-bend is subjected to complete decay or temporary attenuation followed by the complete recovery in the straight tube section downstream from the U-bend. The experimental results show that the downwind propagating through the U-bend was subjected to complete decay or to temporary attenuation with the velocity drop of up to 15–20%.

3. Shock tube design

In this shock tube design we focus our attention on shell structures with an operating pressure below 100 bar. Thus, the shock tube maximal working pressure is designed to be 100 bar whereas the testing pressure is less than 100 bar which are achievable using variable upstream orifice sizes and different locations for the test pieces within the driver section. With a safety factor of 4, the shock tube's designed burst pressure will be 400 bar.

The designed shock tube will operated using pressurised air in the driver section and water in the driven section instead of a gas-gas shock tube option (see Figure 1). The reason is that the dynamic pressure is enhanced when fluid of higher density is used such as water in comparison to air. When the structure is impacted by an explosive shock wave, it responds to the pressure distribution around it. This causes a deflection of the structure, which in turn causes a change in the applied pressure distribution; this once again alters the dynamic behaviour of the structure. This coupled fluid-structure phenomenon continues until the motion of the structure ceases.

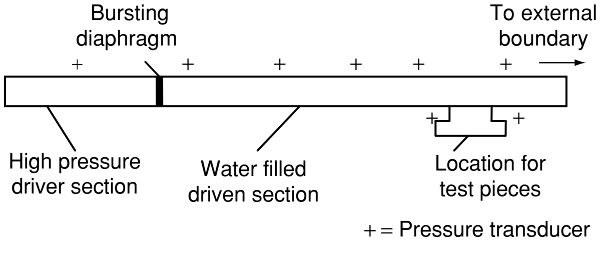

Fig. 1. The shock tube test apparatus.

An important design factor is the time duration of the water impact, when keeping the maximum pressure constant in order to investigate the effect of the pulse width on the structural response. The control of the pulse width in this case is obtained by the expansion wave exit from the end of the tube. Hence, an increase in the testing time (pressure duration) is available by using the expansion wave exit from the end of the driven section, which can be obtained by changing the length of the driven section. Positioning the test piece at various distances from the shock tube exiting end can also alter the amplitude of this transient pressure resulting from the water. In order to increase the testing time (pressure duration) by changing the length of the driven section or change the position of the 'tee' section. The shock tube driven section is composed of three sections of lengths between 1440–1500 mm, joined together with flanges. A standard 'tee' fitting can be placed in different positions and the length of driven section can also be changed if necessary. The shock tube is constructed from type 304 or 316 stainless steel tubing, with the thickness of 7.62 mm, which has a weight of 15.5 kg/m, outer diameter of 88.9 mm, inside diameter of 73.7 mm and with a pressure rating corresponding to Schedule 80 (nominal 170 bar, 2500 psi). The driver section is designed to be 1220 mm long to reduce the amount of driver gas needed to rupture the diaphragms and the overall geometry of the tube is shown in Figure 2.

3.1. Material Selection

The cylindrical pipe can be analysed in a simple manner provided it has a thin wall, then the stress distribution throughout its thickness will not vary significantly, and we will assume that it is uniform or constant. When a thin-walled tube or cylinder is subjected to internal pressure a hoop and longitudinal stress are produced in the wall. The hoop stress can be expressed as:

$$H = pd/2t \qquad (1)$$

Where H = hoop stress (MPa), p = internal pressure in the tube or cylinder (MPa), d = internal diameter of tube or cylinder (mm), t = tube or cylinder wall thickness (mm).

The longitudinal stress can be expressed as:

$$L = pd/4t \qquad (2)$$

Where L = longitudinal stress (MPa).

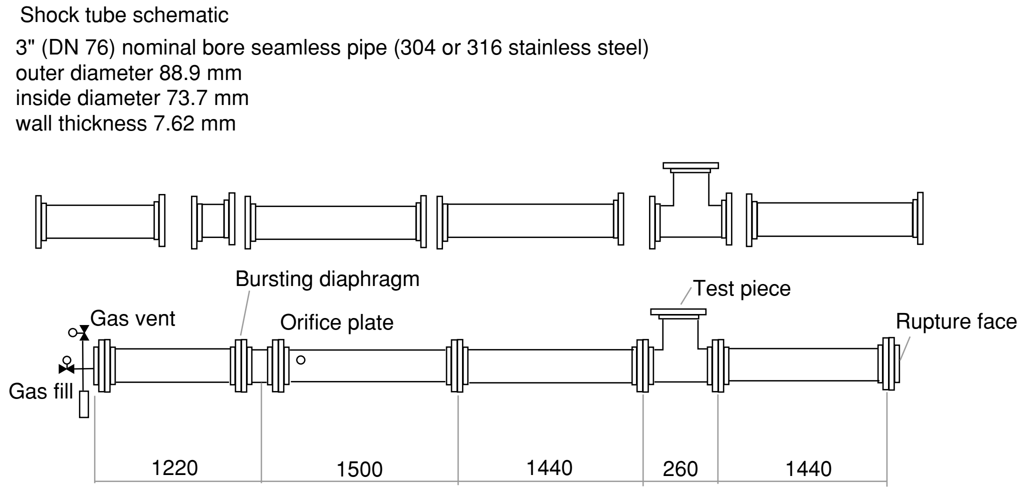

Fig. 2. Setup of the shock tube (dimensions are in mm).

Since the pipe is not closed in the exiting end, therefore, the water cannot develop a loading in the walls in the longitudinal direction. The Schedule 80 rated pressure of 170 bar = 17 N/mm2, and the calculation result of the hoop stress based on the pipe size used is illustrated in Table 1. The inner diameter of the tube is 73.7 mm; the length of driven section in shock tube is 4640 mm. in order to obtain the diameter ratio of 63, which is within the range of 40–100 recommended by (Gaydon *et al.*, 1963). This recommendation is to make sure that the tube is long enough for the shock to fully develop but short enough so that the attenuation of the shock wave does not become a major factor in the experiment.

Stainless steels are iron-based alloys usually containing at least 11.5% chromium. Other elements, nickel being the most important, may be added in combination with chromium to obtain special properties. Stainless steels are highly resistant to corrosive attack and to oxidation at high temperatures. In general, resistance to corrosion and oxidation increases progressively, though not proportionately, with the increase in chromium content. Stainless steel pipe and tubing are used for a variety of reasons: to resist corrosion and oxidation, to resist high temperatures, for cleanliness and low maintenance costs, and to maintain the purity of materials which come in contact with stainless. The inherent characteristic of stainless steel permits the design of thin wall piping systems without fear of early failure due to corrosion. The use of fusion welding to join such piping eliminates the need for threading.

Type 304 stainless is the most widely used analysis for general corrosive resistant tubing and pipe applications. It has a maximum carbon content of .08%. It is not recommended for use in the temperature range between 800°F and 1650°F due to carbide precipitation at the grain boundaries which can result in inter-granular corrosion and early failure under certain conditions. Type 316 is widely used in the sulphite paper industry and for manufacturing chemical plant apparatus, photographic equipment, and plastics. Table 2 shows the tensile strength and yield strength for stainless steel pipe 316/304.316 or 304 Stainless steel pipes 3''(DN 76) will be used in the shock tube experimental setup.

3.2. Flanges and TEE section

The pipe sections are jointed together with SAE flange type for 3'' normal bore. Maximum width (F) 127 mm, maximum height (G) 137 mm, and

Table 1.
Dimension of stainless steel tube with the hoop stress under internal press of 150 bar

Size (in)	Outside diameter (mm)	Inside diameter (mm)	wall thickness (mm)	Identification	sh (N/mm^2)
3	88.90	73.7	7.62	DN76	82.2

Table 2.
Tensile strength and yield strength for stainless steel pipe 316/304

Grade	Tensile Strength (min.)	Yield strength (min.)
316/304 Stainless steel pipe	515 MPa	205 MPa

Fig. 3. SAE flange type for 3'' nominal bore.

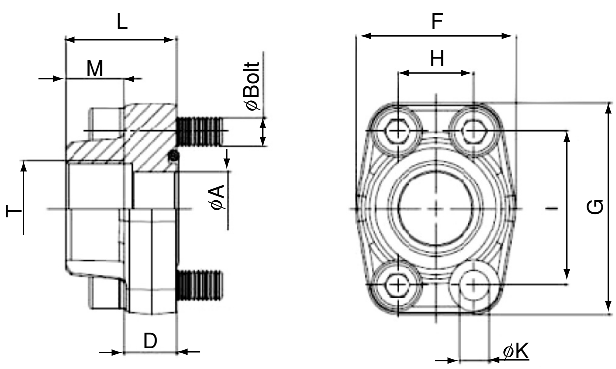

Fig. 4. Engineering drawing of SAE flange 3'' nominal bore.

maximum working pressure 160 bar; thread 3'' BSPP, bolts M16 as shown in Figure 3 and Figure 4.

3.3. Diaphragm and disc

Another important factor in this experiment is that the response of structures to a certain water impact pressure will be investigated in order to establish failure conditions. The desired high pressure in the driven section can be achieved by appropriate choice of the bursting diaphragm. Diaphragms of different materials have different characteristic burst pressures. For a low pressure differential, mylar sheet can be used. When higher pressure experiments are necessary to achieve higher Mach numbers, stainless steel diaphragms of different thickness can be used. For very high pressure differentials, two stainless steel diaphragms can be placed together in one station to achieve double thickness. The metal diaphragm is then etched to allow for a consistent burst. When the etching on each plate is not consistently achieved the burst pressure will be variable and in some cases, the diaphragm may not rupture on both of the axes. In this latter case the pressure rise and shock wave are slower and the flow is not uniform.

Another approach to adjust the driven pressure makes use of a secondary disc that contains a hole at the centre to be placed after the bursting disc. This second disc is placed at least 5 cm downstream from the diaphragm, in order to let the diaphragm bursting cleanly without any obstruction. In this case, hole diameter controls the pressure in the driven section.

3.4. Sensors and other details

Besides the design of the main structure of the driver and driven sections, there are also some instrumentation requirements for the tube. One end of the shock tube is closed to facilitate high pressure in the driver section and the other end is blocked by means of thin film to hold the water before firing the shock tube. On the driven section, there is a short 'tee' branch that can be placed at several positions, to which the test pieces will be attached. The shock tube and 'tee' section are instrumented with pressure transducers and the test pieces are fitted with strain gauges. Pressure transducers are required to be placed as close to diaphragm as possible to monitor the burst pressure and as close as possible to the test piece to detect the acting pressure on test piece. Strain gauge needs to be placed in the centre of circular test piece mounted at test section. Data is collected on a PC using a data acquisition card with sufficient resolution to enable accurate capture of the pressure impact history, see Figure 5. The sensors locations are shown in Figure 2. This driver section is connected by 6 mm steel tubing to a main compressor; the compressor is rated at 100 bar.

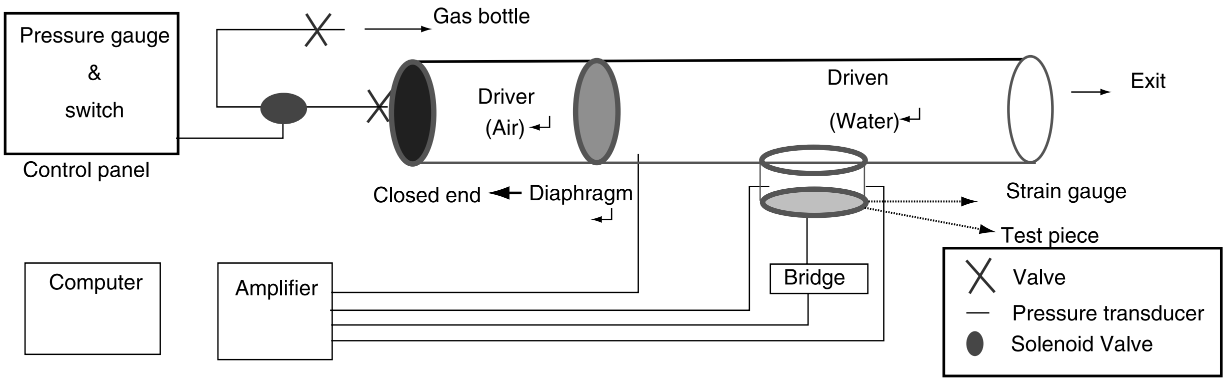

Fig. 5. Schematic diagram of shock tube.

4. Conclusion

In this paper a shock tube experimental setup design is presented with 100 bar maximum pressure requirement with for testing shell structures. The shock tube experimental setup of approximately 6 m with flexibility of moving test section 'Tee section' to three various positions to achieve flexibility in the experiments. The instrumentation of the setup is also discussed for its appropriate operation.

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References

Abrate S., 2005. Impact on Composite Structures. Cambridge University Press. Pp. 312.

Frolov S.M., Aksenov V.S. and Shamshin I.O., 2007. Shock wave and detonation propagation through U-bend tubes. *Proceedings of the Combustion Institute* **31(2)**, 2421–2428.

Gaydon A.G., Hurle I.R. and Kimbell G.H., 1963. Temperature Measurements of Shock Waves and Detonations by Spectrum-line Reversal. IV. Development of Detonations. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* **273(1354)**, 291–305.

Gupta N.K. and Easwara Prasad G.L., 1999. Quasi-static and dynamic axial compression of glass/polyester composite hemi-spherical shells. *International Journal of Impact Engineering* **22(8)**, 757–774.

Haselbacher A.C., Balachandar S. and Kieffer S.W., 2007. Open-Ended Shock Tube Flows: Influence of Pressure Ratio and Diaphragm Position. *AIAA Journal* 45(8), 1917–1929.

Hawyes V.J., Curtis P.T. and Soutis C., 2001. Effect of impact damage on the compressive response of composite laminates. *Composites Part A: Applied Science and Manufacturing* **32(9)**, 1263–1270.

Kugimiya S., Ichizono K., Nourgostar S., Sato K.N. and Kawasaki S., 2004. Development of a new type shock tube without a diaphragm for gas-dynamic laser research. *12th International Congress on Plasma Physics, Nice (France).*

Schokker A., Sridharan S. and Kasagi A., 1996. Dynamic buckling of composite shells. *Computers and Structures* **59(1)**, 43–53.

Skews B.W., Kosing O.E. and Hattingh R.J., 2004. Use of a liquid shock tube as a device for the study of material deformation under impulsive loading conditions. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **218(1)**, 39–51.

Syrunin M.A. and Fedorenko A.G., 2006. Dynamic strength of cylindrical fiber-glass shells and basalt plastic shells under multiple explosive loading. *J. Phys. IV France* **134**, 995–1001.

Tsai S.W. and Wu E.M., 1971. A General Theory of Strength for Anisotropic Materials. *Journal of Composite Materials* **5(1)**, 58–80.

Yu Q. and Grönig H., 1996. Shock waves from an open-ended shock tube with different shapes. *Shock Waves* **6(5)**, 249–258.