Design of a Low-Cost Lab-Scale Shock Tube

Dario Handrick[1], Toma Sucin[2], Victor Dubceac[3], Dylan Homiak[4], and
Wout De Backer[5]
University of South Carolina, Columbia, SC, 29201, USA

Shock tubes provide a more affordable method of producing and studying shock waves than supersonic wind tunnels. A shock wave is a phenomenon which occurs when a wave passes through a fluid faster than the speed of sound in that fluid. This paper aims to explore the conceptual design of a shock tube that can be used in an undergraduate lab environment at the University of South Carolina. This shock tube system should be able to record important shock wave parameters such as pressures, temperatures, and wave speed. Creating and visualizing this phenomenon can be helpful in helping students understand it better. This shock tube is designed based on requirements and constraints following the needs of the aerospace engineering program. The technical aspects of the design process involve various considerations including computational fluid dynamics (CFD) simulation, numerical computation, structural design, and more. The culmination of the research performed within this paper is a plan and design for the manufacture and testing of a shock tube system.

I. Nomenclature

M = Mach number
γ = specific heat ratio
P_1 = driver-side pressure
P_4 = driven-side pressure
a = speed of sound
CFD = computational fluid dynamics

II. Introduction

Shock tube research dates back to the 19th century and has seen widespread application in the study of supersonic flow. The shock tube discussed in this paper is meant to be utilized for educational purposes in undergraduate lab courses. Due to the short timeframe, limited budget, and required simplicity of an undergraduate lab demonstration, the main considerations of this design will be the generation of observable shockwaves, ease of operation, and cost effectiveness. The design considerations taken in creating this shock tube can be broken up into three sections: structural design, computational fluid dynamics, and accompanying systems. The official objective of this project is to design a shock tube to create and analyze compressible flow phenomena in a lab setting with 5 people within 3 months and within a budget of $2250. Our mission needs are to produce shockwaves within a control volume and measure parameters such as pressure and velocity.

III. Shock Tube Theory

Before the design of a shock tube can begin, it is important to understand the fundamentals of compressible flow and shock wave theory. Analyzing a one-dimensional shock wave from the Eulerian perspective, a shock wave is just a discontinuity in the flow resulting in a sudden change in the fluid’s properties. Passing through a shock wave, the

---

[1] Undergraduate Student, Department of Mechanical Engineering, Student Member
[2] Undergraduate Student, Department of Mechanical Engineering, Student Member
[3] Undergraduate Student, Department of Mechanical Engineering, Student Member
[4] Undergraduate Student, Department of Mechanical Engineering, Student Member
[5] Assistant Professor & Faculty Advisor, Department of Mechanical Engineering, Senior Member

fluid velocity decreases while the static pressure, temperature, and density increases. The relationship between these parameters before and after a shock can be derived with the governing equations: mass conservation, momentum conservation, and energy conservation [1]. From these relations, the pressure ratio across a diaphragm can be related to the Mach number and γ of the fluid using Eq. (1). The derivation of this shock tube equation is presented in Ref. [1]. The structural design section of this paper goes into detail about how this equation is used in the design process.

$$\frac{P_4}{P_1} = \frac{2\gamma_1 {M_1}^2 - (\gamma_1 - 1)}{\gamma_1 + 1}\left[1 - \frac{\gamma_4 - 1}{\gamma_1 + 1}\frac{a_1}{a_4}\left(M_1 - \frac{1}{M_1}\right)\right]^{-\left(\frac{2\gamma_4}{\gamma_4 - 1}\right)} \tag{1}$$

IV. Design Requirements

Prior to the beginning of design considerations for this project, it was important to set goals for the project in the form of a constraints and requirements list. Table 1 shows a list of preliminary requirements for our project. A “killer” requirement is one that is necessary for the design to meet, where failure to comply means a significant loss in functionality for the design.

Table 1 Constraints and requirements.

	Constraint	**Means of Compliance**	**C?**	**Killer?**
1	Tube can be no longer than 4m	Measurement	C	Y
2	Design must stay under budget	Budgeting	C	Y
3	Design must include a stand	Design & Manufacturing	TBD	Y
4	Measure shockwaves at speeds of Mach 1.5 or more	Analytical	TBD	N
	Requirements			
1	Have a consistent and replicable diaphragm setup	Testing	TBD	N
2	Design must include a viewing window	Design	C	Y
3	Have a consistent pressurization method	Design & Testing	TBD	N
4	Tube must withstand induced pressure	FEA & Testing	C	Y
5	Design must be simple enough for undergraduate lab use	Research	C	N
6	Design must be finished within 3 months	Delivery of Product	TBD	Y

Several of these requirements and constraints were outlined in our project description. They include constraints 1, 2, and 3, and requirements 2, 5, and 6 from Table 1. The others were discovered in our research of shock tube design. These are self-induced requirements introduced to ensure consistency across experiments; having a consistent diaphragm and pressurization setup will allow for more consistent and reliable results.

V. Structural Design

Shock tubes typically consist of two sections, the driver and the driven section, which are separated by a diaphragm. The driver section is pressurized until a known ratio between it and the driven section is reached and the diaphragm between them ruptures, causing the formation of a shockwave which travels down the driven section, passing sensors and the viewing window.

The main components of this shock tube will be the two steel tubes, adding up to a total length of 4 meters, connected via flanges. The shorter tube section is the driver side, which will be pressurized using a pump. The larger section must be long enough to allow for shockwave development and will house the viewing window and sensors. Both sections will be square tubes with 10.2 cm side lengths and a wall thickness of 6.4 mm made of A500 grade B structural steel. Since we may decide to use a high-speed camera to perform shadowgraph visualization, a viewing window will potentially be installed on the driven side of the tube, meaning calculations will account for this hole in the tube to air on the side of safety. A finite element analysis was conducted using a static structural model in Ansys [2] to ensure these tubes would be capable of withstanding the maximum pressure the chosen pump is capable of (1.1

MPa). The results yielded safety factors of ~ 3.25 for the driver section (Fig. 1) and ~ 2 for the driven section (Fig. 2) including holes for the viewing window and light source.

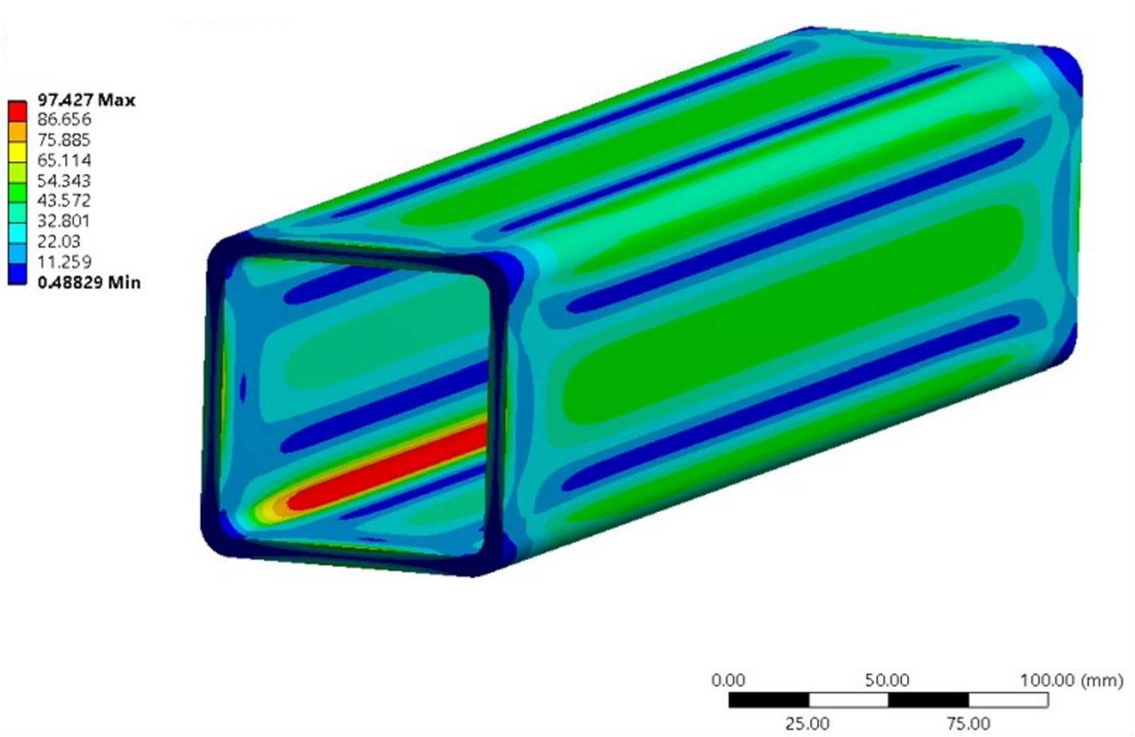

Fig.1 Structural analysis of driver section at 1.1 MPa (material yield stress = 317 MPa).

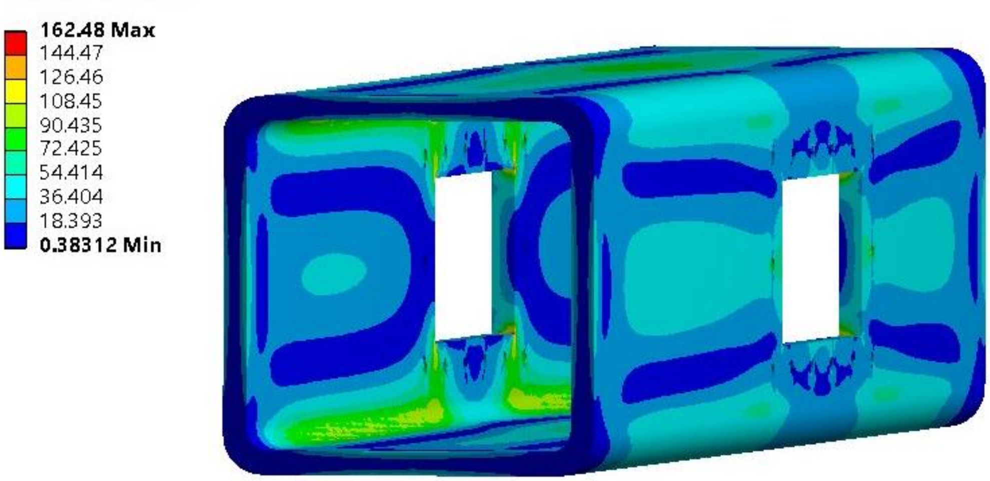

Fig.2 Structural analysis of driven section around viewing window holes (units are MPa).

A. Diaphragm

The two sections will be separated by a diaphragm which, when the proper pressure ratio is reached, bursts to allow for shockwave formation in the driven section. To understand the theoretical relationship between pressure ratio and achieved Mach number, Eq. (1) can be used. Since our shock tube uses ambient air in both the driver and driven section, it is important to note that γ_1 will equal γ_4 and a_1 will equal a_4. From experimental results, however, we determined this equation to be inaccurate. Fortunately, pressure ratio [3], allowing us to estimate a pressure ratio of around 10:1 between the driver and driven section will yield a shockwave moving around Mach 1.5. While creating a vacuum in the driven section could make it easier to achieve higher ratios, this was deemed unnecessary to achieve the ratio and added excessive complexity, since a pressure of 10 atm is not very difficult to achieve. Similarly, some shock tubes use more than one diaphragm to achieve higher pressures and therefore create faster shock waves, but this was deemed not necessary as it would add some cost and complexity. Different diaphragm materials and shapes were compared which could rupture at this pressure ratio. While data on diaphragm burst pressures is limited, a 1 mm thick aluminum diaphragm with a patterned groove was found to burst around 10 atm [4]. Groove depth and thickness for this will be based on the limited existing FEA data [4], but specifically narrowed down experimentally and achieved by hand. In this case, it is important to address that, since the purpose of this shock tube is to be useable in undergraduate lab sessions, ease of use and replaceability of the diaphragms supersedes the need to get a very specific and reliably accurate burst pressure. For this reason, it is not considered worthwhile to machine a specifically grooved diaphragm to ensure highly predictable burst pressure or pattern, if the diaphragm can reliably burst at a pressure which will generate an observable shockwave.

VI. Computational Fluid Dynamics

To guide and validate design decisions, a CFD model was created in Ansys Fluent [2]. This section discusses how the simulation was approached as well as the results of the simulation. Both 3D and 2D models were created, but we found that the results did not differ significantly, so the 2D model was chosen to reduce computation time. The overall approach to modelling a shock tube was inspired by the Sod Shock Tube example from Ansys [5]. The geometry of the tube is a simple rectangle that models the fluid region inside the tube. This simplicity allowed for a dense face mesh to be created for the entire tube without any special considerations. A mesh convergence analysis showed that the simulation became mesh independent around 49,000 elements. The result of this analysis is shown in Fig. 3. The solver used is density based and transient using explicit time integration. This choice was made since shock tube experiments involve compressible flow dynamics over a small amount of time. The air inside of the shock tube is modelled with ideal gas behavior and the k-omega SST model was used to account for viscosity effects. The model does not model diaphragm rupture. Instead, the driver and driven regions are both given an initial pressure and the shockwave begins to form at t = 0 s. The results of the simulations are shown in Fig. 4. The overall behavior of the shock tube appears as expected with the incident shockwave, rarefaction wave, and reflected shockwave travelling according to shock tube theory. The maximum Mach number achieved when simulating a 10:1 pressure ratio is Mach 1.07. This is significantly lower than the value of Mach 1.65 calculated from Eq. (1) and still lower than anticipated after correction based on results from Ref. 4 showing that Eq. (1) produces significant error compared to experimental results [2]. This discrepancy raises doubts about simulation accuracy, but the model still predicts supersonic velocity in the tube. The results from this simulation did not end up providing much insight into the design, they were used as additional motivation to raise the design pressure ratio to 10:1, but also warrant more research into shock tube simulation for future projects.

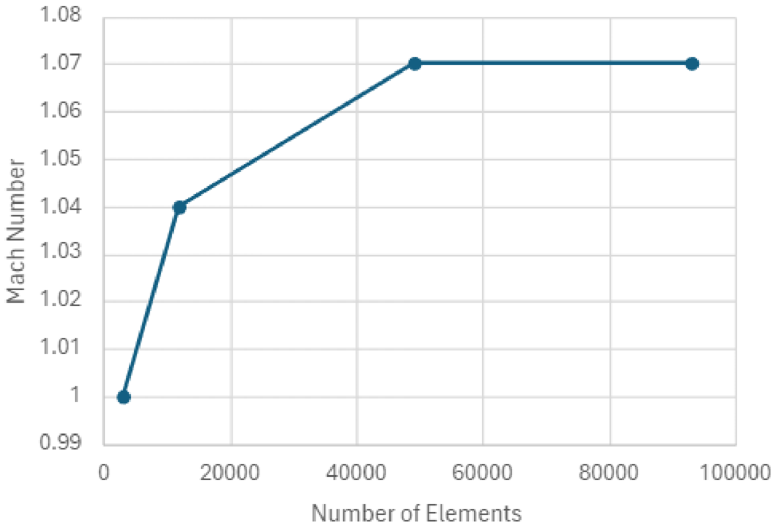

Fig. 3 Mesh convergence analysis of Mach number.

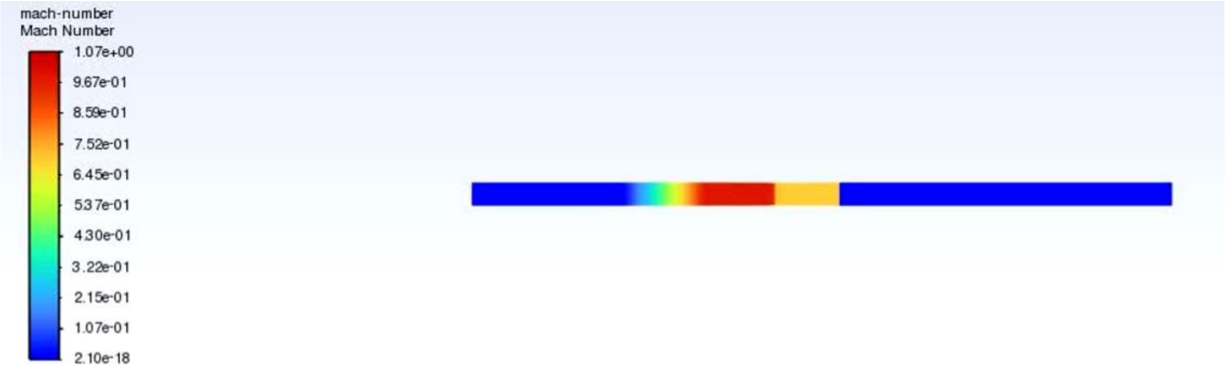

Fig 4. Contour plot showing Mach number along the shock tube.

VII. Systems

The accompanying systems necessary for our shock tube's operation include electrical systems, flow systems, and data acquisition systems. To pressurize the driver section to ~ 10 atm, a standard electric car pump with a maximum pressure capacity of 1.1 MPa (10.88 atm) will be utilized. Measuring the pressure and temperature of the system is important because shock wave behavior heavily depends on these initial conditions. The initial pressure and temperature of the driver gas are recorded with a dial pressure gauge and thermometer, respectively. The driven-side pressure is recorded with piezoelectric pressure sensors for their superior read-rate. The difficulty in velocity measurement lies in the speed at which the shockwave travels, however, from references it can be concluded that piezoelectric sensors are capable of measuring pressure and velocity to a satisfactory degree of accuracy for a relatively low cost [1]. By placing two of these pressure sensors a known distance apart, the velocity of the shock wave can be calculated from the difference in time between each sensor recording the pressure wave. Using the shock velocity, temperature can be calculated numerically. These sensors are powered by a power supply that converts 120 VAC from a standard wall outlet to the voltage required by the piezoelectric sensor.

VIII. Safety Considerations

Because the shock tube being designed is for future use in undergraduate labs, there is extra emphasis on the safety of our project. The pressure vessel is designed with a high safety factor to ensure that there is minimal chance for structural failure. The system is also designed to need little maintenance and to be easy to operate. Additionally, because the driver section is being pressurized to 10 atm, a ball valve has been integrated into the system to allow emergency depressurization, if necessary. In addition to design considerations, operation of the shock tube will only be done or strictly supervised by lab teaching assistants who have been trained thoroughly in the operation and risks of use, and students and instructors will stand at a safe distance away from the end of the tube during operation. Hearing protection will also be a strict requirement for anyone in the lab.

IX. Conclusion

In this project the goal is to create a shock tube for educational purposes for the University of South Carolina Aerospace Engineering Program. The shock tube design meets its goals by proposing a concept which could create observable shockwaves, measure these shock waves, be simple to operate and maintain, and help visualize the theory behind shockwave generation and behavior. The 4 m steel tube utilizing a simple car pump and aluminum diaphragm is a simple yet reliable answer to the desire for an educationally applicable shock tube, which can greatly enhance undergraduate understanding and interest in supersonic airflow. The inclusion of a viewing window and simple piezoelectric sensors allows students to see the phenomenon of shockwaves and apply equations learned in class to calculate values for real life data. With the design of the shock tube complete, the next step is constructing and using it to enhance the educational experience for aerospace students at USC.

Acknowledgments

The authors acknowledge the financial support from the Mechanical Engineering Department at the University of South Carolina. The authors thank Dr. Mostafa Mobli and Dr. Sang Hee Won for their insights and detailed discussions throughout the development of this work.

References

[1] Bergmann, B. E., “Design of an Inexpensive PVC Shock Tube for Educational Use,” *Theses and Dissertations, Rowan University*, URL: https://rdw.rowan.edu/etd/2939/ [cited 3 March 2024].

[2] Ansys Workbench, Ver. 2019 R3, Ansys, Canonsburg, PA, 1970.

[3] Amer, E., Wozniak, M., Jönsson, G., Arrhén, F., “Evaluation of Shock Tube Retrofitted with Fast-Opening Valve for Dynamic Pressure Calibration,” *Sensors*, 29 June 2021.

[4] Lyle, J. L., Guna, K. R., Kumar, P., Sundararaj, A. J., “Rupture dynamics of shock-tube diaphragm,” *2017 First International Conference on Recent Advances in Aerospace Engineering (ICRAAE)*, March 2017.

[5] “Sod Shock Tube – Simulation Example,” Applications of Shock-Expansion Theory, Ansys Innovation Space, URL: https://courses.ansys.com/index.php/courses/applications-of-shock-expansion-theory/lessons/simulation-examples-homework-and-quizzes-applications-of-shock-expansion-theory/topic/sod-shock-tube-simulation-example/, [cited 27 February 2024]