Human Factors and Mechanical Engineering for Defense and Safety (2020) 4: 3
https://doi.org/10.1007/s41314-019-0033-5

ORIGINAL PAPER

Measurement of "Shock Wave Parameters" in a Novel Table-Top Shock Tube Using Microphones

A. Sivakumar[1] · S. Balachandar[2] · S. A. Martin Britto Dhas[1]

Received: 7 June 2019 / Revised: 14 December 2019 / Accepted: 20 December 2019 / Published online: 6 January 2020

Abstract
A new manually operated pressure driven shock tube is proposed and demonstrated. Shock wave-associated parameters like velocity, Mach number, pressure, and temperature are computed using acoustic method. Experiment involves manually loading train of pressure pulses into a driver tube using a bicycle pump. The high pressure buildup in driver tube ruptures the diaphragm at critical pressure and generates a propagating shock wave in the driven section coupled with sensor section in which a couple of microphones are separated by a fixed distance. The propagating shock wave acoustical profile is recorded and its arrival time lag is measured using sound recording software. In a conventional method, piezo-electric pressure sensors are utilized to measure both pressure and time lag of shock wave between the sensors. In the proposed method, microphones are utilized to measure time lag of shock wave with sampling frequency of 768 KHz using computer supporting audio software. Utilizing time data, the said shock wave parameters are evaluated and reported. The performance of the proposed shock tube is compared with manually operated piston-driven Reddy tube.

Keywords Table-top shock tube · Bicycle pump · Mach number · Acoustic method velocity · Microphone

Introduction

Development of table-top shock tubes is one of the current interest [1, 2]. The shock waves produced by such shock tubes find applications in many fields including aerospace, biomedical, food processing, and material characterizations for extreme condition applications [2–10]. It has the advantages of being simple, safe, and capable of producing shock wave. Usually, in table-top shock tube, piezo-electric pressure gauges are utilized to measure the pressure and velocity of shock wave. The major cost of manually operated table-top shock tube is mainly depending on the cost of pressure gauge and data acquisition system. The knowledge of shock wave parameters such as velocity, Mach number, Mach angle, pressure, and temperature is mandatory for the specific applications in material science. In this article, a new design of manually operated table-top shock tube is proposed, and the shock wave parameters are determined using a novel cost-effective acoustic method. The piezo-electric pressure gauges and data acquisition system which are used in the conventional shock tubes are replaced by microphones controlled by sound recording software. In the proposed method, measurement of pressure of the shock wave is eliminated and the resolution of Mach number is improved. From the measured Mach number, shock wave parameters are reported with better resolution and the performance of the proposed manually operated shock tube is compared with manually operated piston driven shock tube for single and double layer diaphragm [7].

Highlights
✓ A new manually operated pressure-driven table-top shock tube using a bicycle pump is developed and tested.
□ Shock wave related parameters are estimated using a microphone.
□ Proposed shock tube is capable of producing Mach number above 2.
□ Cost-effective method and suitable for laboratory/ research purposes.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s41314-019-0033-5) contains supplementary material, which is available to authorized users.

✉ S. Balachandar
balachandar.dr@gmail.com

[1] Department of Physics, Abdul Kalam Research Center, Sacred Heart College, Tirupattur, Tamilnadu 635601, India

[2] Department of Research and Development, AKSH Optifiber limited, Bhiwadi, Rajasthan 301019, India

Proposed Table-Top Shock Tube

Conventional shock tube consists of three sections, namely driver section, driven section, and diaphragm section which couples the other two sections. Compressor generates high-pressure driver gas in the driver section. At critical pressure, it ruptures the diaphragm, creating shock layer, and it travels into the driven section. The strength of the shock wave is governed by a material of the diaphragm and its thickness. High-energy shock tube requires metal diaphragm with thickness in the range of a few centimeters. In the table-top shock tube, trace paper of thickness 0.01 cm, with 80 GSM, acts as a diaphragm, capable of producing Mach number of 1.5. Manually operated piston-driven shock tube was reported by Reddy and Sharath, in-which plunger in the driver section was pushed manually until diaphragm ruptures. Pressure of the shock wave is recorded using digital storage oscilloscope with piezo-electric pressure gauges. Shock tube performance parameters are estimated using one-dimensional normal shock relations [7].

The proposed "manually operated shock tube" is capable to produce Mach number above 1.5. The proposed shock tube also consists of three sections: (1) input section, pressure pulse using a bicycle pump; (2) shock tube section; and (3) sensor section, microphone controlled by software as shown in Fig. 1.

In the proposed method, a manually operated bicycle pump is utilized to buildup pressure in driver section. Operation of a bicycle pump involves up-stoke and down-stoke of reciprocating piston. During up-stoke, the manually operated piston draws air from ambient (outside) into the cylinder of the bicycle pump, and during down-stoke, the piston displaces the air from the pump into driver section of the shock tube. These alternating stokes continues until enough pressure builds-up in driver section to rupture the diaphragm. In the proposed approach, high pressure can be loaded in driver section compare with manually operated "piston driven shock tube." The shock wave which produced due to the rupture of diaphragm, travels through driven section, and subsequently passes through sensor section. Sensor section consists of two microphones for the measurement of velocity of shock wave. The distance between two microphones is sufficiently long to distinguish the arrival time of the shock wave for the given sampling frequency. The schematic diagram of proposed experimental setup is shown in Fig. 2. Control of sampling frequency, sound-record on/off, and basic post signal processing like filter and smoothening can be done by computer through software.

Dimension of Proposed Shock Tube

The proposed shock tube is a miniaturized version of a conventional shock tube. Along with driver section and driven sections, it consists of two additional sections, namely input section and sensor section. The dimensions of driver section, driven section, sensor section, and distance between two microphones are illustrated in Fig. 3. The internal diameter and external diameter of the shock tube are 1.5 cm and 1.9 cm, respectively.

Operation of Proposed Shock Tube

Pressure of the driver gas (air) in the driver section is gradually increased by a manually operated bicycle pump. The input is fed continuously until diaphragm ruptures, which leads to generation of shock layer traveling in driven section, and subsequently into sensor section. In sensor section, two microphones will pick up transient pressure signal. The spatial separation between two microphones along the axial direction is utilized to measure the velocity of traveling shock wave in shock tube. The difference in arrival time between the two microphones is measured by from the recorded waveforms.

Acoustic Method for Estimation of Shock Tube Parameters

In the conventional method, piezo-electric pressure sensors are utilized to measure the pressure of the shock wave and the arrival time of the shock wave between two pressure sensors. The resolution of the time data depends on sampling frequency of analog-to-digital convertor. Generally, the sampling frequency is 200 KHz and the separate hardware is developed for acquiring pressure signal [11, 12]. Therefore, the cost of the data acquisition system is higher than the proposed acoustic technique. In the proposed method, shock waves are treated as

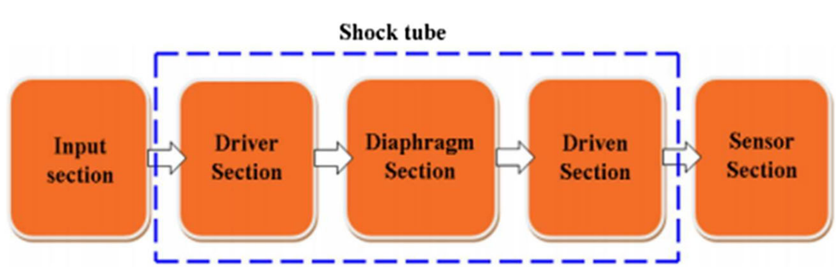

Fig. 1 Block diagram of proposed pressure-driven shock tube

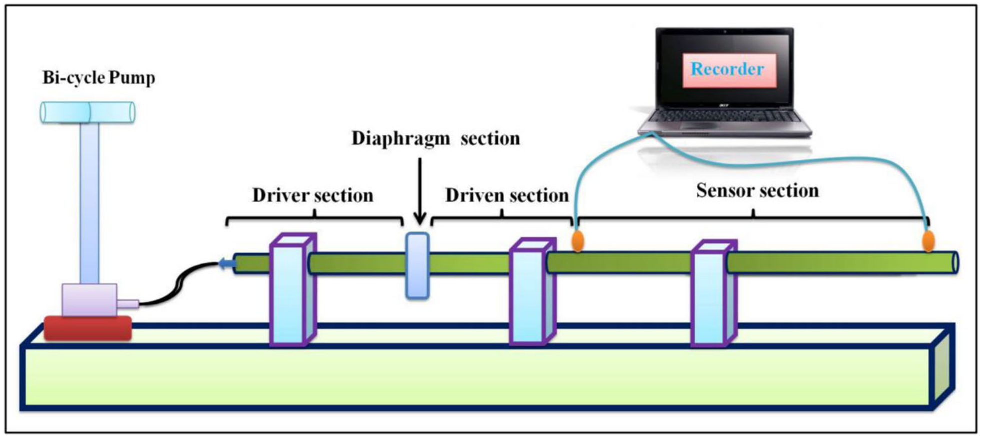

Fig. 2 Schematic diagram of the proposed shock tube

acoustic waves, so using a microphone the shock wave is recorded. The audio jack is connected to a computer, using a software of the following parameters are controlled: (a) sampling frequency (shock wave is sampled at 786 KHz) and (b) sound record on/off. Hence, time resolution is improved to milliseconds. It is well known that acoustic method is utilized for (a) computing bullet-velocity and Mach number, and (b) characterize the trajectory of the projectile shock wave [13, 14]. In this article, the shock wave parameters like velocity, Mach number, pressure, shock wave angle, and temperature of proposed shock waves are evaluated based on acoustic method. Using an acoustic method time lag of shock wave is measured with high resolution, and the said parameters are computed.

Estimation of Mach Number

The experiment to generate shock wave is conducted with prescribed initial and boundary conditions: (a) driver gas and driven gas are ambient air, (b) initial pressure is ambient pressure (1 bar), (c) initial temperature is ambient temperature (300 K), (d) diaphragms are trace papers of thicknesses of 0.01 cm and 0.02 cm. Velocity of sound (Vs) at ambient temperature (Ta) in degree centigrade (°C) is given by [11].

$$Vs = 331\ m/s + 0.6\ (m/s{*}C){*}Ta \tag{1}$$

Using the above equation, the velocity of sound at 27 °C is 347.2 m/s. The velocity of the shock wave is calculated from the ratio of "distance between the microphones to the time delay between them (time delay is 0.0022 s). Mach number (M) is the ratio of measured velocity and the velocity of sound in air medium and it is found as 2.2. Time resolution is increased to sub-milliseconds that facilitated by in-built analog-to-digital convertor in the computer whereas in conventional method, external hardware is mandatory. Standard deviation and error calculations of the measurement values are presented in the Table S1.

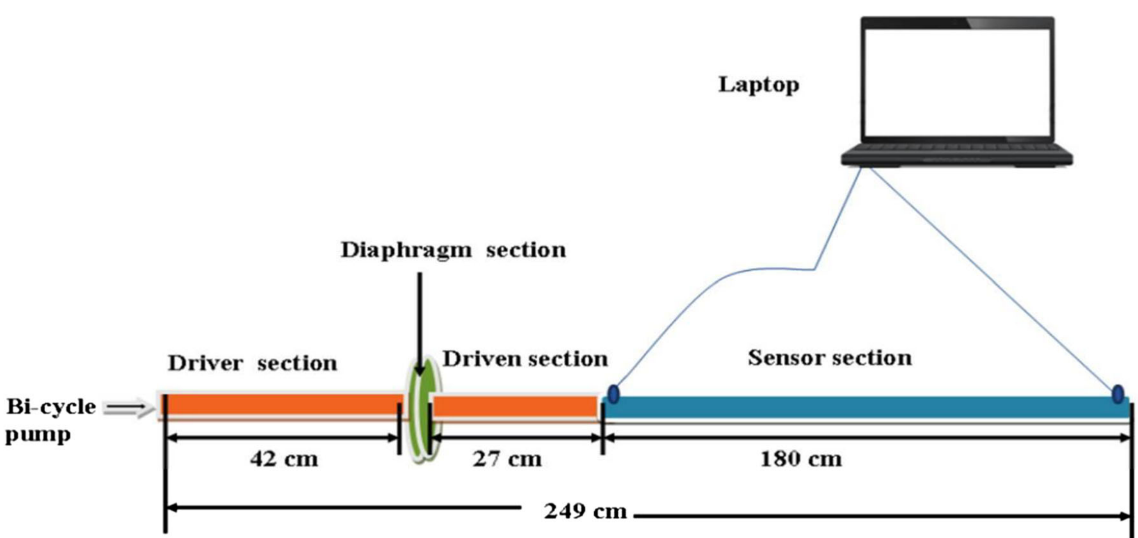

Fig. 3 Schematic diagram of the shock tube with dimensions

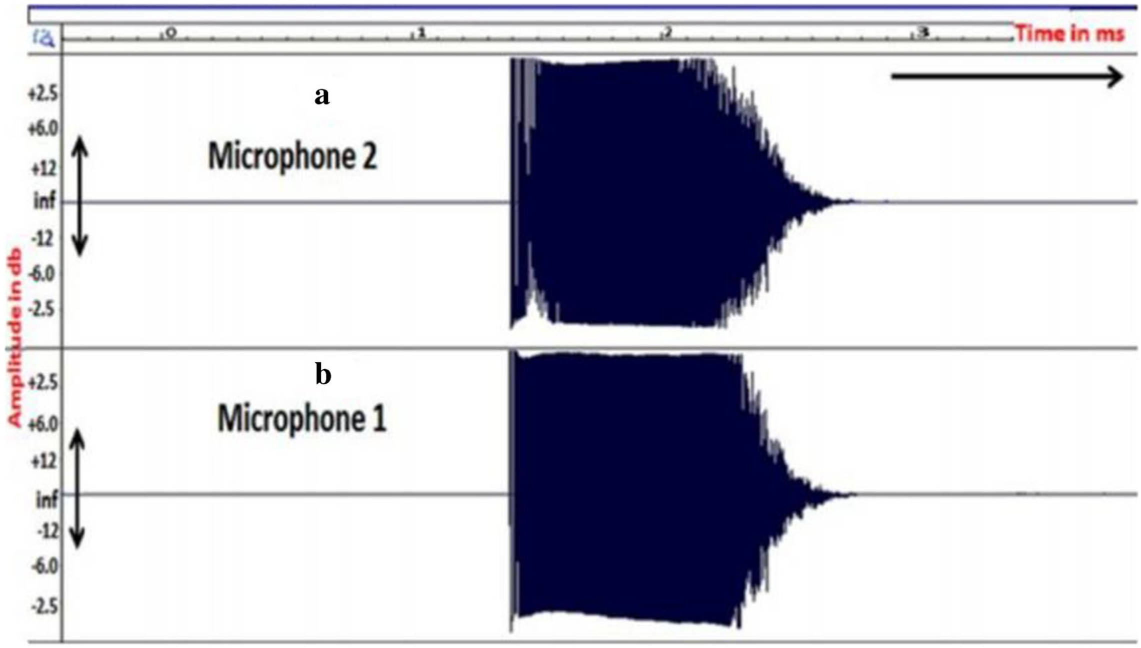

Fig. 4 Shock wave produced by single layer diaphragm of thickness 0.01 cm. a) Recorded by microphone2 and b) recorded by microphone1

Shock Wave Recorded by Microphones

The experiment involves a couple of identical microphones placed in sensor section, controlled by a computer with the sound forge software version 6.0. Shock wave is recorded with sampling frequency of 768 KHz with 32-bit resolution. Initially, both driver tube and driven tube are at ambient pressure with ambient temperature, and diaphragm separates both the sections. Before diaphragm ruptures, no significant output is recorded in microphone1 and microphone2. Due to high pressure in the driver tube, the diaphragm ruptures and the shock wave propagates into the driven section. Subsequently, sensor section and the waveform recorded by microphone1 and microphone2 (for single "layer trace-paper-diaphragm") are shown in Fig. 4 a) and b), respectively.

Waveform recorded by microphone1 and microphone2, for double layer diaphragm, is shown in Fig. 5 a) and b), respectively. Figures 4 and 5 indicate that the pulse width is double for "double layer diaphragm" than the single layer diaphragm. The time lag is

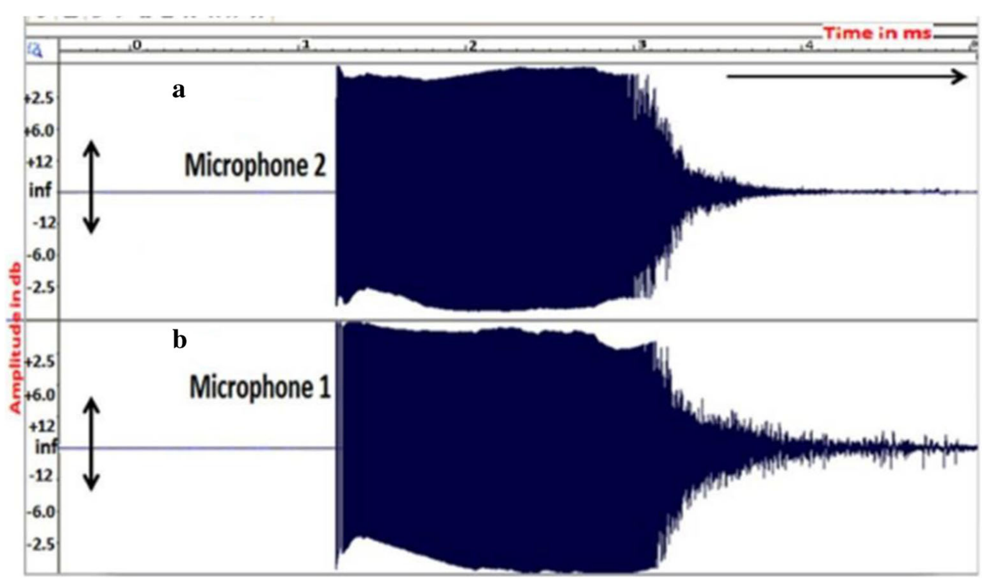

Fig. 5 Shock wave produced by double layer diaphragm of thickness 0.02 cm. a) Shock wave recorded by microphone2 and b) recorded by microphone1

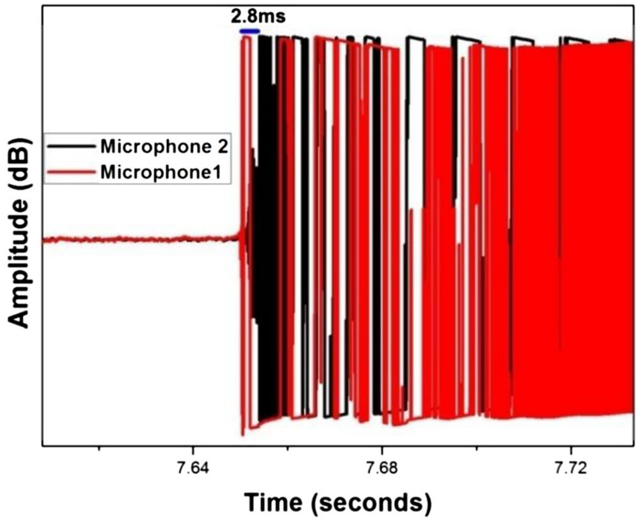

Fig. 6 Time delay of the shock wave recorded by the microphones

calculated between first peak of shock wave recorded by microphone 1 and microphone 2, respectively. Figure 6 shows the time delay of the acoustic shock wave between the microphones.

Estimation of Shock Wave Parameters

Using one-dimensional normal shock relations [7], the inter-relationship among the shock wave parameters is calculated and the values are presented in Table 1.

The results reported in the above table indicates that the velocity, Mach number, and rupture pressure P_4 are higher for double layer diaphragm compared with single layer diaphragm.

Table 1 Shock tube dimension and shock wave parameters for single and double layer diaphragms

Parameters	Reddy tube	Proposed shock tube	
		Single layer	Double layer
Diameter of the shock tube (cm)	2.9	1.5	1.5
Diaphragm thickness (cm)	0.01	0.01	0.02
Velocity (m/s)	513	664 (± 9)	784 (± 9)
Mach number (M)	1.47	1.91	2.26
Initial pressure(P_1) (bar)	1	1	1
Temperature(T_1) (K)	300	300	300
Pressure (P_2) (bars)	2.35	4.08	5.786
Temperature(T_2) (K)	389	484	570
Pressure (P_5) (bars)	5.02	12.8	21.96
Temperature (T_5) (K)	489	699	891
Pressure(P_4) (bars)	6.3	32.32	75.02

Conclusion

A new "manually-operated bicycle pump based table-top shock tube" is proposed and demonstrated. An acoustic method is introduced in which conventional piezoelectric pressure sensors are replaced by cost-effective acoustic sensors called microphones, and eliminates measurement of absolute pressure. The obtained results indicate that the Mach number is estimated with better resolution, the shock wave parameters are estimated using time data, and the performance of the proposed shock tube is compared with Reddy tube. The preliminary results of the proposed shock tube are presented for both single and double layer diaphragm. The proposed shock tube is more suitable for low energy applications like shock therapy, biomedical, aerospace, and material stability characterizations. Also, this shock tube is suitable for school and college level laboratory experiments on shock waves.

Funding Information The authors thank the management of Sacred Heart College for the financial support through Don Bosco Research Grant (SHC/DB Grant/2017/01).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Sudhieshkumar C, Reddy KPJ (2015) Experiment in hand-operated, hypersonic shock tunnel facility. Shock Waves 26:845–849. https://doi.org/10.1007/s00193-015-0608-x
2. Swietek B, Santhakumar V, Pfister B (2012) Table-top air pressure-driven shock tube toinduce a blast traumatic brain injury. IEEE 51-52(2012). https://doi.org/10.1109/NEBC.2012.6206957
3. Paterson RF, Lifshitz DA, Kuo RL, Siqueira TM Jr, Lingeman JE (2002) Shock wave lithotripsy monotherapy for renal calculi. Int Braz J Urol 28:291–301
4. Nossair AA, Eid MM, Salama AB (2013) Advanced protocol of shock wave therapy for diabetics foot ulcer. Am J Sci 9:633–636
5. NguyenTT N, WilgerothJ M, Proud WG (2014) Controlling blast wave generation in a shock for biological application. J Phys Conf Ser 500:142025. https://doi.org/10.1088/1742-6596/500/14/142025
6. Courtney E, Courtney A, Courtney M (2014) Shock tube for high intensity blast waves for laboratory testing of armor and combat material. Defen Tech 10:245–250. https://doi.org/10.1016/j.dt.2014.04.003
7. Reddy KPJ, Sharath N (2013) Manually operated piston-driven shock tube. Curr Sci 104:172–176
8. Kalaiarasi S, Sivakumar A, Martin Britto Dhas SA, Jose M (2018) Shock wave induced anatase to rutile TiO2 phase transition using pressure driven shock tube. Mater Lett 219:72–75. https://doi.org/10.1016/j.matlet.2018.02.064
9. Sivakumar A, Suresh S, Anto Pradeep J, Balachandar S, Martin Britto Dhas SA (2018) Effect of shock waves on dielectric

properties of KDP crystal. J Elect Mater 17:4831–4839. https://doi.org/10.1007/s11664-018-6362-y
10. Sivakuamr A, Martin Britto Dhas SA (2019) Shock wave induced nucleation leading to crystallization in water. J Appl Cryst 52:1016–1021. https://doi.org/10.1107/S1600576719009488
11. Courtney M (2008) Acoustic methods for measuring bullet velocity. Appl Acoustic 69:925–928. https://doi.org/10.1016/j.apacoust.2007.05.004
12. Yuldashev P, Karzova M, Ollivier VKS, Blanc-Benon P (2015) Mach-Zehnder interferometry method for acoustic shock wave measurements in air and broadband calibration of microphones. J Acoust Soc Am 137:1–11. https://doi.org/10.1121/1.4921549
13. Chang H, Wu Y-C, Tsung T-T (2011) Characteristics and measurement of projectile shock waves by a 32- microphone ring array. Rev Sci Instrum 82:084902. https://doi.org/10.1063/1.3622044
14. Padhy S, Panigrahi S (2014) Measuring projectile velocity using shock wave pressure sensors. Def Sci J 64:499–501. https://doi.org/10.14429/dsj.64.8108