SHORT COMMUNICATION

Shock tube data processing tools using open source hardware and software platforms

K. Thirumalesh1,2 | Salgeri Puttaswamy Raju3 | Hiriyr Mallaiah Somashekarappa4 | Kumaraswamy Swaroop4

1Department of Physics, Mangalore University, Mangalore, India
2Department of Physics, R L Jalappa Institute of Technology, Bengaluru, India
3Department of Physics, Malnad college of Engineering, Hassan, India
4Center for Application of Radioisotopes and Radiation Technology (CARRT), Mangalore University, Mangalore, India

Correspondence
K. Thirumalesh, Department of Physics, R L Jalappa Institute of Technology, Doddaballapur 561 203, Bengaluru, Karnataka, India.

Abstract
To cater the need of specific shock-tube data acquisition and processing system, a low cost open-source alternative has been developed and presented in this paper. Using easily available open-source hardware and software platforms such as ARDUINO, a robust 5.3 MHz speed data acquisition system along with optimized shock tube data processing software is designed and an indigenous shock tube data processing tool has been developed. This has been found to be 10 times less cost than the general-purpose computing equipment available on the market, with a substantial reduction in shockwave data processing time and effort. The setup has been tested with the different diaphragms producing shockwaves of different Mach numbers. The experimental results are compared with the theoretical values obtained using normal shock relations and are found to be consistent with admissible error limits. This validates the design and construction of the device for scientific experiments.

KEYWORDS
Arduino, open source, shock tube, shock tube data processing, shockwaves

1 INTRODUCTION

Shock waves are the wave instances which are produced when a sudden burst or expansion takes place in a fluid medium.1,2 Technically, shockwave is a narrow surface that manifests as a discontinuity in a fluid medium in which it is propagating with supersonic speed. The shockwave is characterized by an abrupt or nearly discontinuous increase in pressure, temperature and density of the medium through which it propagates.3 When a shock wave is formed, a distinct surface is created by the medium itself which is known as shock wave-front. A typical shock front thickness is just a few micrometers and the entire physical changes take place within this small volume known as control volume.4 Like an ordinary wave; shockwave also carries energy and propagates through any material medium such as solid, liquid, gas or plasma. The impact of shock waves on any surface is a momentary effect. But, it may create sustainable changes due to very high pressure, temperature and other physical condition changes.4 Depending on the changes in pressure and temperature inside the shock front, shock waves are classified as strong or weak.

The potential of shock waves to produce nonlinear pressure and temperature surges in the medium of propagation, finds exciting applications in diversified fields, such as, extraction of juice from fruits and vegetables,5,6 the design and
modeling of an aircraft,\textsuperscript{7} insertion of DNA into a biological cell,\textsuperscript{8} treatment of heart,\textsuperscript{9,10} kidney stones,\textsuperscript{11} and so on. Also, the applications extend to the material processing,\textsuperscript{12-16} manufacturing and other industries.\textsuperscript{4,17-19} Therefore, to get more applications out of shockwave phenomenon; it is very much required to produce shock waves in the laboratory or industry in a controlled manner. The instrument used to produce shockwaves in laboratory in a controlled manner is known as a shock tube or a shock tunnel.\textsuperscript{3,20-22} The recent works of Reddy and Sharath,\textsuperscript{21} demonstrated a miniaturized shock tube capable of producing low magnitude shock waves; which is the main motivation for this work. Many institutions and researchers across the country are using this device for the academic and research works.

Along with a shock tube, a high-precision oscilloscope with data logging facility is needed for the analysis of the data obtained from it. The oscilloscopes or data loggers are the general-purpose equipment which are multi-functional and having more capacity that may not require for this purpose. Furthermore, it takes considerable amount of time and human expertise to process the data from these devices and get the required results. Also, the cost of such instruments restricts the usage of shock tubes in low-budget research projects. Therefore, it is very much essential to develop handy and cost-effective tools to produce and process shockwaves in the laboratory. In this regard, we have designed specific shock tube data processing tools using open source platforms like ARDUINO\textsuperscript{23} PROCESSING\textsuperscript{24} and simple sensor technology to get the cost effectiveness. The work presented here; not only minimize the processing time and human effort but also offers a cost-effective technique that provides a state-of-art data acquisition and processing facility for a shock tube or tunnel.

2 | SHOCK TUBE AND DATA PROCESSING

2.1 | Shock tube parameters

Generally, the shock tube consists of a driver section, a driven section and an arrangement with a thin diaphragm separating the two.\textsuperscript{2,3} When a high pressure is created by the compression of the air medium in the driver section, the diaphragm ruptures by producing a shock wave in the driven section. The shock produced will move with supersonic speed which is measured in terms of Mach numbers. Mach number is a unit used to represent the speed of an object. It is defined as “the ratio of the speed of the object to the speed of the sound in the air medium.” Thus, Mach 1 refers to the speed of an object, which is same as the speed of sound in the air medium and more than 1 represents the speed of the object which is equal to the multiples of that number with the sound speed. The supersonic speed shockwave data is sensed through a set of high frequency piezoelectric pressure and temperature sensors attached with the shock tube.\textsuperscript{4,21,25} This data is recorded with the help of a high speed data logger for further processing. The Mach number of the shock wave produced can be determined from the time plots of the recorded data. The plot would consist of two peaks separated by a distance on a time scale. The difference between these peaks will give the time taken by the shock wave to travel between the two sensors separated by a distance. With known distance of separation of sensors, we can calculate the velocity of the shock wave and there by the Mach number. Also the diaphragm rupture pressure can be noted from the pressure gauge/sensor attached. With this data the other parameters like pressure and temperature jump at the primary shock wave-front and reflected shock wave-front can be calculated using normal shock relations or R-H equations as given below.\textsuperscript{4,21}

The relation between the pressure jump of the primary shock wave front ($P_2$), the initial driving gas pressure ($P_1$) and the Mach number ($M_S$) is,

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}(M_S^2 - 1)$$  \hspace{1cm} (1)

The relation between the ratio of temperatures of primary shock wave front ($T_2$) to the initial driving gas temperature ($T_1$) and Mach number ($M_S$) is,

$$\frac{T_2}{T_1} = \left[\frac{2 + (\gamma - 1)M_S^2}{(\gamma + 1)M_S^2}\right] \times \left[1 + \frac{2}{\gamma+1}(M_S^2 - 1)\right]$$  \hspace{1cm} (2)

Also, the relation between the ratio of initial driver gas pressure (rupture pressure, $P_4$) to initial driven gas pressure ($P_1$) and Mach number ($M_S$) is,

$$\frac{P_4}{P_1} = \frac{2\gamma}{\gamma+1} \left[1 - \frac{\gamma - 1}{\gamma+1} \left(M_S - \frac{1}{M_S}\right)\right]^{-\left(\frac{\gamma}{\gamma - 1}\right)}$$  \hspace{1cm} (3)

Where $\gamma$ is the specific heat ratio of the gas and $M_S$ is the Mach number.
2.2  Construction of the shock tube

The present work has been focused on an in-house developed shock tube which is a simplified foot-pump operated and is capable of producing shockwaves of Mach number up to 2. But, for the same tube, if a good air compressor is used or a compressed Helium gas as driver medium then it is possible to get higher Mach numbers, probably it will be up to 5 or 6. Thus, the system is a low pressure operated compared to a large shock tunnels (input pressure of the gas is less than 500 psi or 35 bar) but good enough to produce shock waves of Mach number up to 2.

The schematic diagram of the modified shock tube of the present work is shown in Figure 1. And the actual photograph of the developed device shown in Figure 2.

The shock tube is made up of 316 grade stainless steel tube having 20 mm inner and 38 mm outer diameter. The driving section is around 400 mm length and driven section is around 500 mm length. The selection of the material is based on its durability, non-corrosive property. The other dimensions are based on the convenience and availability of the material in the market. Both the driver and driven sections are joined with the help of a threaded cup arrangement. The cup fitted with a handle to load the diaphragm between the sections easily.

The other major enhancement in this device is the addition of a specific processing device and software. To achieve cost effectiveness, open source hardware and software platforms like ARDUINO and PROCESSING are used. A high speed data acquisition system and an interfacing software tool which gives the necessary results by processing the data acquired from the shock tube are developed.

2.3  Shock tube data processor—The hardware

The equipment developed for processing the data obtained from the shock tube is based on ARDUINO. Arduino is an open source computer hardware and software platform that develops and produces single-board microcontroller kits to create digital devices that can, sense and control objects in the physical world. Arduino development platform were used to develop several inexpensive, automated sensing and data logging systems for use in research projects.26,27

---

**FIGURE 1**  The schematic diagram of the modified shock-tube

**FIGURE 2**  Actual photograph of the modified shock-tube developed
The processing device is based on Arduino Mega 2560, which is a microcontroller board based on the Atmel processor ATmega2560. It contains everything needed to support the microcontroller. The block diagram of the hardware part is shown in Figure 3.

The input signals from the three pressure sensors or shock sensors, which are having the shock movement information, are fed to an Analog to Digital converter (ADC) circuit which converts the analog voltage signal into six bit digital data and then transmits the data to a 16 MHz clock speed Arduino Mega processor. This is good enough to read and process the signals generated during the shock wave travel. Meanwhile, the diaphragm rupture pressure is sensed by a pressure sensor and the data is transferred to the Arduino Mega. All the consolidated data is supplied to a PC through an USB cable. At PC the data is processed and the results are displayed with the help of a software tool developed. The data flow diagram of the entire process is given as supplementary information.

The Arduino Uno/Mega’s ADC typically delivers a speed of about 200 kHz at 10 bit resolution. But this is far-low, since it operates at a clock speed of 16 MHz. This is because of the number of clock pulses needed to run a hardware-level instruction. We cannot achieve what we actually need at this pace. Further, by using some direct register access techniques we can increase it up to 1 MHz, but it is still much lower than the required. Therefore, in order to achieve expected goal, the alternate solution is to use a high speed external ADC and make Arduino to read these data at its maximum speed. For this purpose a 6 bit ADC of *Intersil* make “CA3306” was chosen (Any other ADC with 8 MHz and above with higher resolution will also works well). Because, it can reach up to 15M samples per second and gives parallel output. 6 bit in this case may seem low resolution, but it is good enough for our purpose. Because, the sensors that we are using are switch type sensors not pressure sensors. The signal that we get is a flat saturated amplitude signal (Figure 5). Therefore, whether it is 6 bit resolution or 24 bit does not make any difference. For better performance of ADC, instead of using external clock signal, the clock signal generated at one of the Arduino output pins is used as the clock input. Since ATmega2560 processor work with 16 MHz clock it is possible to get 8 MHz clock from one of its output pins. To achieve this, we need to bypass some high level programming instructions and have to use machine level assembly instructions by addressing the input/output ports directly. The sample instructions used to achieve this is as given below.

To set 8 MHz clock signal on Arduino mega pin 11 of PORT A.

```
TCCR1A = _BV (COM1A0); /* toggle OC1A */
TCCR1B = _BV(WGM12) | _BV(CS10); /* CTC, no pre-scaling */
OCR1A = 0; /* Clock output */
```

This piece of code will generate an 8 MHz signal at output pin number 11. This signal is used as clock input for the external ADC.

The Arduino is programmed such that it reads the data from the ADC at its maximum speed using direct port addressing techniques instead of normal high level programing instructions. In Arduino Mega, PORT F is used as analog input/output port. So, the data values are read directly from the PORT F, without using any loop statements as given below,

```
Shock_Data.Values[0] = PINF;
Shock_Data.Values[1] = PINF;
Shock_Data.Values[2] = PINF; etc 
```

A structure of more than 3 Megabytes of data containing all the sensors data will be transferred to the PC for further processing. This structure or data packet will be having the snap of the shock wave instance which travels through the sensors. Also, the structure contains the time stamp of the first byte and last byte reading from ADC. The difference...
between these two time stamps will be used to calculate the sampling frequency. Typically, the structure will have 3600 bytes of data from the ADC and the time difference between the data reading of these number of bytes is 676–680 μs (Table 1). Therefore, the time to fetch each byte of data is around 0.19 μs. Thus, the sampling frequency of these data becomes around 5.3 M Bytes per second.

### 2.4 Sensors

The device consists of three shock sensors for detecting shock motions and one absolute pressure sensor for monitoring diaphragm rupture pressure $P_4$. In which the first sensor ($S_1$) acts as trigger, which give signal to the processor to grab the shock movement data through the other two sensors ($S_2$ and $S_3$). So, when a shock wave propagates through these sensors, we get two peaks as output from the software tool developed specifically for this shock tube. From this, we can measure the time delay between the peaks, which is nothing but the time taken by the shockwave to travel between these two sensors ($S_1$ and $S_2$). As the distance between the sensors $S_2$ and $S_3$ is 10 cm fixed (as convenience), we can calculate the speed of the shockwave and there by the Mach number.

The sensors which sense the shock movement in the shock tube play a very important role in this project as they are the key elements. Any high speed pressure sensors will serve the purpose, but our goal is to reduce the cost of the project. So, we tried to develop and use some home-brew shock sensors. After many trial and error methods we come up with a sensor module which is as shown in Figure 4(A),(B).

The sensor module is based on high speed linear/binary Hall Effect magnetic sensor ICs like A1324 of Allegro make or SS49E of Honeywell make and a 4 mm $\times$ 1.5 mm Neodymium magnet. When a shock front propagates through the sensors the pressure wave pushes the light weight permanent magnet and creates a magnetic field variation linking the Hall Effect sensor. This in turn generates an electrical signal which is directly depends on the variation in the magnetic field. This signal will be picked up and converted to digital data with the help of the ADC circuit. There will be three such sensors in the driven section, they are used to detect the shock propagation time. The first sensor acts as a trigger to snap the shock propagation through the remaining two sensors. This method eliminates the waiting time before the shock and also reduces the amount of data to be collected, making the data processing easy and quick.

#### Table 1 Experimental results for different diaphragms

| Diaphragm of different thickness | Data sampling time in μs | Time between the peaks in μs | Velocity of shockwave generated in m/s | Mach number | Diaphragm rupture pressure $P_4$ in bar (experimental) | Diaphragm rupture pressure $P_4$ in bar (theoretical) |
|---------------------------------|--------------------------|------------------------------|---------------------------------------|-------------|-------------------------------------------------------|------------------------------------------------------|
| Art Paper—75 GSM               | 676                      | 221.562                      | 451.34                                | 1.3         | 3.458                                                 | 3.14                                                  |
| Art Paper—90 GSM               | 676                      | 196.645                      | 508.53                                | 1.46        | 4.732                                                 | 5.37                                                  |
| Art paper—120 GSM              | 680                      | 185.830                      | 538.12                                | 1.55        | 6.552                                                 | 7.53                                                  |
| Art paper—180 GSM              | 680                      | 180.022                      | 555.48                                | 1.59        | 9.014                                                 | 8.59                                                  |
| Laminated art paper—300 GSM    | 676                      | 164.601                      | 607.52                                | 1.74        | 13.231                                                | 13.88                                                 |

#### Figure 4 The shock sensor module (A) Schematic (B) Actual photograph (C) PCB holding Hall Effect sensor

PCB with Hall sensor
Permanent magnet
2.5  |  Error factor and limitations

Since this is an analog type of sensor, there are few things to be considered in order to extract meaningful data from it. The main cause of error in this system is the time lag due to the movement of the magnet. By making the magnet movement as free as possible, and selecting the magnetic material as light as possible, this error can be minimized. Also, it is found that there is no considerable difference in the weight and structure of the magnets. With all these considerations, there might be still some time delay in the signal. This can be neglected because the same amount of time delay will be produced in the second sensor also. So the entire shock pattern will be advanced by this amount of error. In addition, if there is any error in time due to unequal sensor switching times, it can be identified and measured by taking few consecutive test shots by switching the first and second sensors and comparing the readings. Thus, it is found that with all these precautions and tests, the error in the readings is about 10–30 μs with respect to total reading, which is around 5%–16% for the average reading. In any shock tube measurements there will be always some error either in the diaphragm rupture pressure measurement or the time delay measurements due to various reasons. Thus, the measured error is similar when compared to standard devices used in shockwave experiments. The only limitation of the sensors is; the readings are not proportional to the pressure rise of the shockwave front. Therefore, the primary or reflected shockwave pressure jump, $P_2$ and $P_3$ cannot be measured.

2.6  |  Shock tube data analyzer—The software

To process the data obtained from the sensors and to produce the shock profile outputs, an indigenous software tool “Shock Tube Data Analyzer” is developed using open-source software development environment—PROCESSING. The tool has all the features required to process the shock tube data. When a snap of a shock is received from the device, immediately it gives the shock profile output, which will be having two peaks separated by a distance. The peaks correspond to the movement of the shock wave through the second and third sensors. A typical snap of the output of a shock profile is given in Figure 5. When the mouse is dragged between the peaks, we get the time between the peaks in microsecond and it is nothing but the time taken by the shock wave to travel between the sensors. With this data we can find the Mach number of the shock wave as the distance between the sensors is known (it is 10 cm for the device tested). Also we can get the value of the rupture pressure $P_4$, on screen. This is obtained from the pressure sensor attached with the shock tube in the driving section. By using the value of the Mach number and the rupture pressure it is possible to calculate other...
characteristic parameters of the shock wave, like peak temperature T₄, reflected shock pressure and temperatures, and so on, by using R-H equations or normal shock relations (Equations (1)–(3)).

The software tool also has the feature of storing the entire shock profile data into a file and reading it back again. This would be useful for later reference. Also, it has the ability to give shock profile outputs in pdf and jpg formats which would be helpful for publications.

3 | CALIBRATION AND RESULTS

The calibration of the device is done by comparing the experimental results with the theoretical values obtained from the nonlinear R-H equations (Equations (1)–(3)). The typical output obtained for an art paper diaphragm is given in Figure 5.

From the data it is found that the time interval between the peaks is 182.8444 μs and the distance between the sensors is 10 cm. Therefore, the speed of the shockwave is found to be 546.9 m/s. The speed of sound wave is calculated using the Newton’s formula, \( v = \sqrt{\gamma RT} \), where \( \gamma \)—the specific heat ratio(1.4), R—the gas constant(287 J/kg) and using temperature \( T = 300 \) K, the speed of sound at normal temperature is found that 347.18 m/s. Thus, the Mach number, \( M = \frac{u}{v} \) is 1.57.

The experiment is repeated with different diaphragm materials and thickness. The typical values obtained for different diaphragms producing shockwaves of different Mach number are given in the Table 1. The results are plotted along with the theoretical plot as shown in Figure 6. It is in good agreement with theoretical values as it is evident from the plot of the ratio of the rupture pressure (P₄) to initial pressure (P₁) versus Mach number.

The theoretical calculations are done with R-H equation, where: P₄—diaphragm rupture pressure, P₁—initial driven gas pressure, \( \gamma \)—the specific heat ratio, and M—The Mach number of the shock wave generated.

The deviations from the expected values in certain cases are due to the error in the measurement of time delay from the sensors and may be due to the error in the measurement of rupture pressure P₄. This is in accordance with the standard devices and procedure.3,4,21

4 | EXPERIMENTATION

Using the above described setup, series of experiments were conducted to study the effects of shock wave treatment on different materials. Among them, study of shock wave impacts on Poly (vinyl alcohol) - PVA films13,14 were very much fruitful and got remarkable achievement in significant increase in the electrical conductivity13 and increase in the water contact angle by an amount of 110°, making the material from hydrophilic to hydrophobic.14
5 | CONCLUSION

Using freely available open-source hardware and software tools, a low cost shock-tube facility has been set up with indigenous shock-tube data processing equipment and shock-tube data analyzer software. The processor is a 5.3 MHz speed Ardunio Mega based device, capable of sensing supersonic speed shock movements. The analyzer software is capable of producing shock profile outputs with shock speed calculations. The work presented is unique in its kind and is proved to be 10 times less cost than the general purpose equipment in the market. The system has been calibrated and tested for the reliability. With an average error percentage ranging from 5 to 16% for the total reading, it is found consistent in performance, over time and multiple runs. Thus, the results are optimistic and endorse the process and technique used for scientific investigations. The device is used in several shock wave research experiments and the results are published in well-known journals (Section 4—Experimentation). Further experiments are in progress to test the device for higher magnitude shockwaves and other applications.

ACKNOWLEDGMENT

We are very thankful to Mr. Uday of SLN EduTech, for the technical support in making the idea a reality.

PEER REVIEW INFORMATION

Engineering Reports thanks Raza Qazi and other anonymous reviewers for their contribution to the peer review of this work.

DATA AVAILABILITY STATEMENT

The source codes that support the findings of this study are openly available in 'github' online repository at https://github.com/ThirumaleshK/Shocktube.git.

CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

AUTHOR CONTRIBUTIONS

Thirumalesh K: Conceptualization-Lead; Investigation-Lead; Methodology-Lead; Resources-Lead; Software-Lead; Writing-original draft-Equal. Raju S.P.: Data curation-Equal; Investigation-Equal; Methodology-Equal; Writing-original draft-Equal. Somashekarappa H.M.: Project administration-Lead; Supervision-Lead; Validation-Equal; Writing-review and editing-Lead. Swaroop K: Formal analysis-Equal; writing-review and editing-Equal.

ORCID

K. Thirumalesh https://orcid.org/0000-0002-4791-9749

REFERENCES

1. Hurle IR. Chemico-physical processes in shock waves. Reports Prog Phys. 1967;30(1):149-187.
2. Payman W, Shepperd WCF. Explosion waves and shock waves VI. The disturbance produced by bursting diaphragms with compressed air. Proc Royal Soc. 1946;A186:293.
3. Morgan R. Free piston driven expansion tubes. In: Ben-Dor G, ed. A Handbook of Shock Waves. Vol 1. New York, NY: Academic Press; 2001.
4. Kumar CS, Takayama K, Reddy KPJ. Shock Waves Made Simple. Vol 1. New Delhi: Wiley India; 2014.
5. Jagadeesh G. Industrial applications of shock waves. Proc IMechE G J Aerosp Eng. 2008;222(G5):575-583.
6. Kuraya E et al. Improving the antioxidant functionality of citrus junos Tanaka (yuzu) fruit juice by underwater shockwave pretreatment. Food Chem. 2017;216:123-129.
7. Carrera E, Morello V, Valletti D, Algoistino F. Simulation of shock wave impact due to explosion on a flying flexible aircraft. Combust Explos Shock Waves. 2007;43:732-740.
8. Jagadeesh G, Takayama K. Novel applications of micro-shock waves in biological sciences. J Indian Inst Sci. 2002;82:49-57.
9. Holfeld J, Lobenwein D, Tepeköylü C, Grimm M. Shockwave therapy of the heart. Int J Surg. 2015;24(1):218-222.
10. Loske AM. Medical and Biomedical Applications of Shock Waves. 1. Switzerland: Springer International Publishing; 2017.
11. Chaussy C, Schmiedt E, Jocham D, Brendel W, Forssmann B, Walther V. First clinical experience with extracorporeally induced destruction of kidney stones by shock waves. J Urol. 1982;127:417-420.
12. Rita A, Sivakumar A, Martin Britto Dhas SA. Influence of shock waves on structural and morphological properties of copper oxide NPs for aerospace applications. J Nanostruct Chem. n.d. 2019;9:225-230.
13. Thirumalesh K, Raju SP, Somashekarappa HM. Study on effects of shockwave treatment on PVA films in view of electrical property changes. Mater. Res. Express. 2020;7:015344.
14. Thirumalesh K, Raju SP, Somashekarappa HM. Shock wave treated PVA films as alternative bio degradable polymer for packaging industry. J. Electro. Phys. 2020;12(2):02034.
15. Jayaram V, Hegde GM, Hegde MS, Reddy KPJ. Paper presented at: 26th Int. Symp. On Shock Waves; 2007; Gottingen, Germany: Springer:159–164.
16. Jayaram V, Hegde MS, Reddy KPJ. Paper presented at: 24th Int. Symp. on Shock Waves; 2004; Beijing, China: Institute of Mechanics.
17. Reddy KPJ. Making shock waves pay: the commercial aspects of shock waves. Paper presented at: 30th International Symposium on Shock Waves; 2017: Springer.
18. Nanda SR, Agarwal S, Kulkarni V, Sahoo N. Shock tube as an impulsive application device. Int J Aerosp Eng. 2017;2017:1-12. https://doi.org/10.1155/2017/2010476.
19. Nataraja G, Jagadeesha KN. Applications of shock waves in agriculture research. Int J Aerosp Innov. 2009;1(1):23-30.
20. Davis HJ, Curchack HD. Shock Tube Techniques and Instrumentation. Washington, DC: U.S. Army Material Command, Harry Diamond Laboratories; 1969.
21. Reddy KPJ, Sharath N. Manually operated piston-driven shock tube. Curr Sci. 2013;104(2):172-176.
22. Reddy KPJ, Kumar CS, et al. Hand-operated shock tube and hypersonic shock tunnel. Fluid Mech Res Int. 2018;2(4):144-146.
23. An Open-Source Electronics Prototyping Platform. Arduino; n.d. http://www.arduino.cc.
24. An open source programing environment. PROCESSING; n.d. https://processing.org/.
25. Ben-Dor G, Igra O, Elperin T. Handbook of Shock Waves. 1. Amsterdam: Academic Press - Elsevier; 2001.
26. Fisher D, Gould P. Open-source hardware is a low-cost alternative for scientific instrumentation and research. Modern Instrum. 2012;1(2):8-20.
27. D’Ausilio A. Arduino: A low-cost multipurpose lab equipment. Behav Res Methods. 2012;44:305-313.
28. Paun M-A, Sallese J-M, Kayal M. Hall effect sensors design, integration and behavior analysis. J Sens Actuator Netw. 2013;2:85-97.

SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Thirumalesh K, Raju SP, Somashekarappa HM, Swaroop K. Shock tube data processing tools using open source hardware and software platforms. Engineering Reports. 2021;3:e12353. https://doi.org/10.1002/eng.212353