



An Optical Measurement System to Measure Velocity and Provide Shock Wave Pressure Diagrams

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ABSTRACT

This paper introduces an optical measurement system for shock wave characteristics. The system works by mounting a metal plate attached to spring mounts against the shock wavefront. This set is sealed and can plot the shock wave pressure diagram by measuring plate's displacement, radiation and changing the reflection of light during shock wave conflict, and converting these optical data to voltage. In the experiments with the optical system, there was no delay time in the wave impact response. Using the optical system and the fixture designed and built, it is also possible to measure the velocity of moving objects and monitor the planar shock wave formation in addition to the shock wave velocity. Then the calibration was performed with the help of a standard piezoresistive sensor in a cold diaphragm shock tube, with a pressure of 5.5 to 12.5 bar by performing 12 tests. Relations and figures for output voltage and shock pressure are also explained.

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1. INTRODUCTION

Scientists have studied shock wave as a phenomenon for years. Some have studied the shock wave to prevent possible destruction and reduce its damages, and some aimed at generating it and using its high energy for various activities. What is being discussed initially in terms of the shock wave is the way of developing it as well as sensors with very high time sensitivities to measure shock wave properties.

The need for explosives is one of the limitations of shock wave generation. For years, scientists have attempted to provide the possibility to generate a shock wave without the need for explosives by using the shock tubes. Even with explosives, the generation of fully controlled and uniform shock waves is tough that the shock tube

can easily provide. One of the applications of the shock tube is sensor calibration [1]. In the regular shock tubes, there are two high-pressure (driver) and low-pressure (driven) gas areas which are separated by a diaphragm. Pressure in the high-pressure area depends on

the thickness and material of the diaphragm. By increasing the pressure of the driver and the instant rupture of the diaphragm, the shock wave is generated [2]. This increase is achieved by a variety of methods including explosion [3, 4], combustion [5], or high-pressure gas tank [6, 7].

Because the pressure generated in a shock wave has a considerable variation in amplitude (rise time), the design and manufacturing of sensors to measure these specifications are essential. In all of these sensors, the changes of a fundamental physical quantity are first measured, and then the changes are converted to presentable and searchable values with the help of converters. In a sort of classification, these sensors are divided into two groups of "detection of the moment of shock wave arrival and the measurement of velocity" and "pressure measurement sensors" [8].

The first group of sensors are time detectors with laser [9], cinematography [10], X-ray flash [11], electromagnetic sensors, shadowgraph, high-speed cameras, Schlieren [12, 13], and other innovative techniques [14], which are also visible in some of these

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methods such as the high-speed cameras, Schlieren, and some laser methods, as well as the shape of the wavefront. In all of these methods, the need for an external supply is to receive changes from the sensor. The main disadvantage of these sensors is the lack of direct measurement of pressure since the pressure is the main characteristic of the shock wave.

The second group of sensors consists of piezoresistive and piezoelectric sensors. Piezoresistive materials are those which resist changes properly with pressure change. These materials are used for pressure measurements in quasi-static experiments. For the first time in 1921, Chiese manufactured the piezoelectric measurement instrument. These sensors are now among the most common sensors to measure the shock wave pressure [15], which also has a high cost and a need for expertise to use. They also require amplifiers and processing and cannot measure negative pressure.

In this paper, the shock waves are generated by a diaphragm shock tube called KNTU1. This shock tube is the cold type (without combustion and explosion) that supplies pressure (up to 20 MPa) with a high-pressure gas tank. Due to the need to investigate the pressure in the experiments, the optical sensor was designed and manufactured in an entirely innovative manner in addition to quick dynamic response and high precision in measurement, light weight and small size, low manufacturing cost, and ease of use; it is also an optical sensor with the ability to measure the positive and negative pressures of the shock wave. This sensor with innovation in the working model can measure the pressure and can be used by calibration with the piezoresistive sensor in the shock tubes and obtaining voltage conversion function. In addition to pressure measurements, the sensor can also measure the velocity of the wave. Besides, it can also measure the velocity of moving objects. A diaphragm shock is used for sensor calibration. In this paper, we describe the different parts of this measurement system and operational procedure, the method, and the results of calibration by the shock tube and finally some of its applications.

2. MATERIALS AND METHODS

2. 1. Designing and Manufacturing the Optical Sensors

This measurement system was designed and constructed by using the idea of Oliver et al. [16]. In this sensor, an electric kit could detect the distance between the plate and the fiber head by producing and transmitting light using a fiber optic to a metal plate. A metal plate with a glossy surface was mounted on a spring at a certain distance from the optical fiber head in the probe (Figure 1). The plate faced the shock wave and moved with the wave pressure.

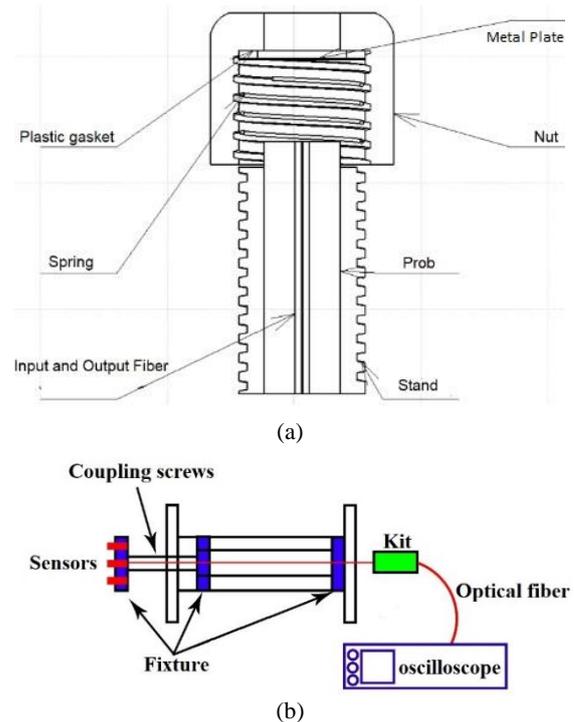


Figure 1. A) Schematic head of an optical measuring system and B) Schematic of measuring system

The displacement of the plate causes a change in the amount of reflected light. The electrical circuit converts it into an electrical signal (voltage) by receiving this change and checking the amount of light received. The output of the electrical circuit is inserted into an oscilloscope or data logger so it can be monitored. By calibrating the measuring device with the standard sensor, the corresponding pressure of the output voltage was obtained, and the pressure change diagram was plotted. Practically with the start time of the displacement in hand, shock wavefront reaching time could also be calculated. Then by placing several sensors in different coordinates of a specific cross-section of the wave and obtaining the wave arrival time in each sensor, the shape of the shock wavefront could be investigated.

The striking point is the repeatability of sensors and their identical and similar outputs. To prove the repeatability of sensors, the normalized voltage-displacement diagram is obtained, which was similar for all sensors, as shown in Figure 2.

As it is shown in the diagram, in 1.5 to 2.5 mm distance between the surface and the head of optical fibers, the diagram is linear, and this means allowing the plane to move in this range to obtain the correct output.

To perform tests, the plate was placed in 2.2 mm of the fiber. Under these conditions, the plate could get closer to the fiber up to 0.7 mm (1.5 mm distance) or get away from it up to 0.3 mm (2.5 mm distance) to remain in the linear variation range.

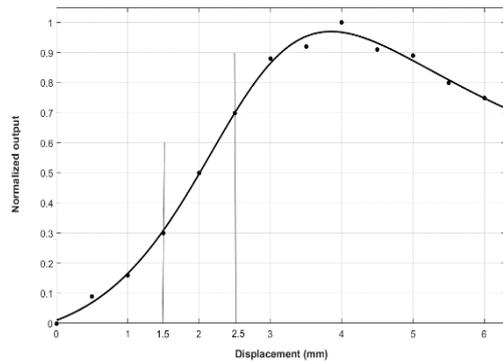


Figure 2. Voltage changes due to spring displacement

- The characteristics of this measurement system can be referred to as:
- High speed of measurement to measure the positive and negative pressures of the shock wave
- Adjustable for pressure at different intervals
- Lack of disturbance by the ambient noise
- Measuring the time of arrival and shock wave velocity
- Measuring the velocity of moving objects
- Displacement along the driven shock tube
- Repeatability
- Availability and cost-effectiveness

This system consisted of three main parts: the first part, which consisted of the sensor head and optical fibers transmitted the data of sensor head into the second part, which was an electronic converter and the converter converted the optical data into electricity by connecting to the power supply, and by wire to the third part, which was the representation part. In this section, which was used from a data logger or oscilloscope, the output results were received and then analyzed.

In order to position the sensors at the end of the shock tube, there was a need for the fixture. Since one of the main objectives in the use of sensors was to investigate the uniformity and profile of shock wave pressure, the aluminum fixture with the necessary resistance calculations was designed to provide sensor location in most of the cross-sectional area.

The forehead part of this fixture had 18 holes. These holes could install the sensors (Figure 3). It is essential to note that if the number of sensors increased and the effective diameter of their sensitive surface decreased as much as possible, the shock wave profile could be plotted with the help of the computer.

The shock wave recorded by this measurement system is shown in Figure 4. As it is known, the sensor could measure negative pressure as well as positive pressure of the shock wave, since when the metal plate connected to the spring was exposed to tension, the plastic gasket was compressed, and a slight elastic



Figure 3. Fixture for positioning sensors at the end of the shock tube

deformation occurred at the plane, which could develop a long distance from optical fibers and record the negative pressure.

3. RESULTS

3. 1. Examining the Response Delay Time of the Optical Sensor One of the critical points for sensors which measure the shock wave is the delay at the beginning of a function. The delay means the time difference between arriving shock wave and the first change in output voltage.

To measure this delay, the piezoresistive sensor and optical sensor (Figure 5) were fixed in a part of the shock tube in which it was sure that the shock wave was formed, and both sensors were connected to an oscilloscope. In this experiment, the pressure was 9.5 bar, and the distance from the diaphragm was 275 cm, and nitrogen gas was used.

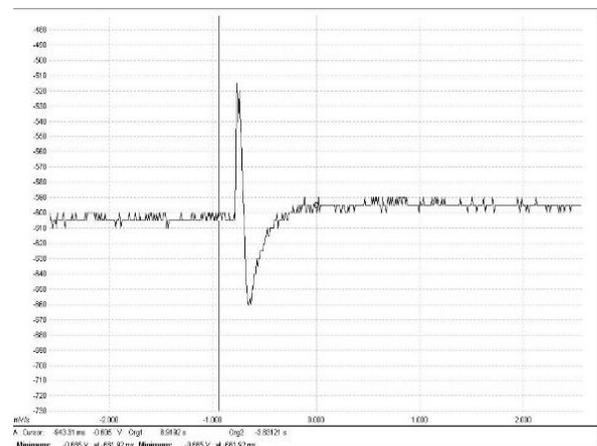


Figure 4. Optical sensor output in shock records

As can be seen in the diagram, the beginning of voltage change in sensors occurred at the same time. This time is the response time of sensors for shock wave to reach to sensor diaphragm. Since the response time of the synthesized optical sensor was the same with a piezoresistive sensor, it can be concluded that optical sensor delay is acceptable.

3. 2. Measuring Shock Wave Velocity by the Optical Sensor

One of the applications of the developed optical sensor is measuring the velocity of the shock wave in the tube. In order to do this, two optical sensors should be used simultaneously in the shock wave tube, such that sensors are fixed in the tube with two different distances from the diaphragm and are placed against shock waves. Shock wave velocity can be obtained from the response time of the two sensors and distance of two sensors from each other.

Figure 6 shows an example of measuring shock wave velocity. In this test, which was done by the driver pressure of 10 bar, the distance of two sensors from each other was 45 mm. As can be seen in the figure, the shock wave reaches to both sensors in 71.87 microseconds. Thus, wave velocity is 1.82 Mach with sensors placed at 45 mm distance from each other.

The difference in peak voltage in the above diagram is due to the distance between two sensors, and in fact, it shows shock wave pressure at two different positions. Since sensor No.1 is closer than sensor No.2, the shock wave reaches to it in a shorter time and has more pressure in this position.

The sensors are located at two different distances from the diaphragm. Since the wave energy is damping and decreases during movement through the shock tube, the first sensor has a higher peak point than the second sensor.

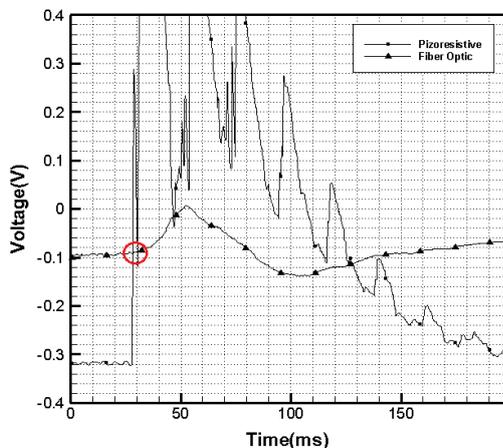


Figure 5. Delay time in two optical and piezoresistive sensors

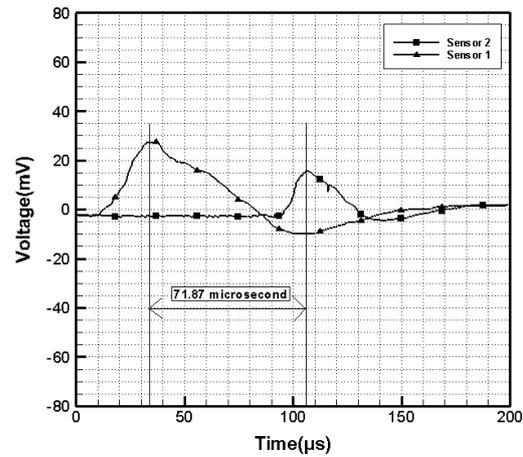


Figure 6. Results of two optical sensors at a distance of 45 mm from each other

3. 3. Measuring the Velocity of High-speed Objects

Another application of the above optical fiber measurement system is measuring the velocity of objects. By putting two sensors in a certain distance and removing plate and spring at the top of the sensor, the reflected light to the sensor will change when an object passes a sensor in a dark space. The beginning of these changes is when the object reaches the sensor. Thus, object velocity can be calculated by the time that the object reaches two sensors and the distance between two sensors. For example, the optical sensor was used for measuring the velocity of a pneumatic valve placed in the KNTU2 shock tube instead of the diaphragm, in which 10 milliseconds was needed to open the valve. As shown in Figure 9, the valve was initially closed, and the first sensor was in front of it, and the second sensor was at the bottom of the valve. In this state, during the valve opening, each of the sensors receives the voltage difference caused by the light's impact on the valve. The voltage of the first sensor climbs up with the movement of the handle, and the second sensor shows a drop in the voltage as the handle reaches the valve.

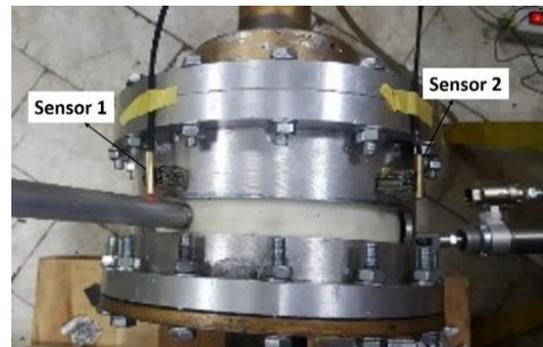


Figure 7. Sensor status on the pneumatic valve

An example of received diagrams in the oscilloscope is seen in Figure 8. The time needed for opening value and the velocity of the opening was calculated by using these diagrams and calculating the distance of arrived waves from sensor No.1 and sensor No. 2 in the oscilloscope.

3. 4. Detecting Plane Form of Shock Wave

In order to examine uniformity and plane form of the shock wave, a sensor was placed at the center of the fixture, and two more sensors were placed randomly at other points. Thus, if the shock wave loses its spherical form and becomes like a plate, the beginning time of output signal from three peripheral sensors is the same as the output signal from the central sensor. However, if the shock wave is not uniform in the traveled distance, the beginning point of the diagram is different for sensors, and the central sensor receives the signal sooner. Figure 9 shows an example of sensor output for uniform waves.

3. 5. Calibration of The Measurement System and Measuring Shock Wave Pressure

To calibrate the optical sensor, optical sensor and reference sensor should be placed close to each other in different pressures when arriving shock wave. Then, outputs resulted from these tests should be compared, and a logic relationship between them should be obtained by using computer programming.

In the other words, it was tried to find a diagram and relationship for each sensor to convert the sensor output voltage to shock wave pressure. In order to provide an acceptable range in this relationship, sensors were placed at four certain distances from the diaphragm in the KNTU1 shock tube, and three different pressures were used at each distance along with a change in diaphragm thickness. For this, twelve tests were done.

In the KNTU1 shock tube (Figure 10), the maximum pressure at the driver point was 150 bar, and the driven pressure was 1 bar equal to atmospheric pressure. The

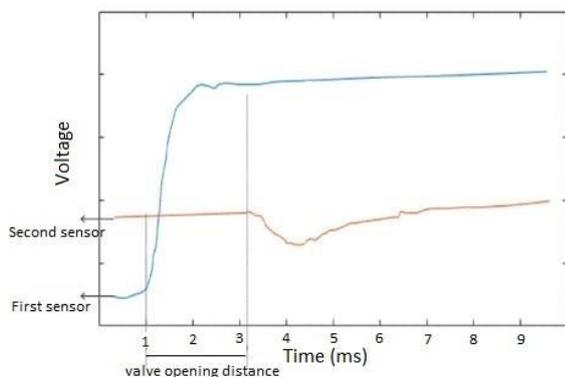


Figure 8. Waveforms received from sensors in an oscilloscope (Blue line is related to Sensor 1 and red line, Sensor 2)

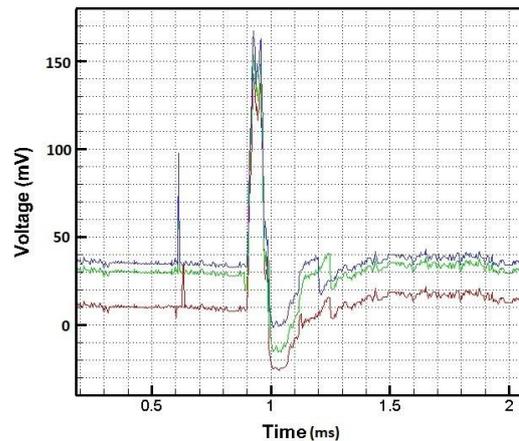


Figure 9. Results of the three optical sensors inside the shock tube

driver length was 1.2 m and the driven length was 3.5 m, and nitrogen gas was used in this tube.

The diaphragm used in the current study was Mylar diaphragm that was made of a type of polyester, which was also known as polyethylene terephthalate. Table 1 presents the physical characteristics of this polyester.

In the current study, Endevco piezoresistive 8530B was used as a reference sensor. The active part of the sensitive surface was made of silicone, and its diameter was 2 mm. Figure 11 shows an example of the piezoresistive sensor used in this study. The amplifier used in this study was Endevco Amplifier 136, which was a three-channel DC amplifier that could be programmed manually or by computer. Therefore, three piezoresistive sensors and two optical sensors were placed at different points on the fixture, and the amplifier was installed. Finally the results of testing the pressure in the tube were shown as output voltage by all sensors by installing an amplifier to signal processor devices. The piezoresistive sensor used in this study had a conversion factor equal to

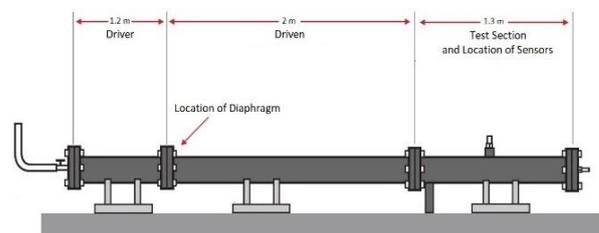


Figure 10. Schematic of KNTU shock tube

TABLE 1. Physical properties of PET polyester [17]

Tensile strength	Shear impact strength	Thermal expansion coefficient	Melting point	Density
2.5 N/mm ²	1.5-3.5 kJ/m ²	6.55E-4 1/K	250-256 °C	1.335 g/cm ³



Figure 11. Endevco model 8530B piezoresistive converter

1.379, which means that the pressure of the desired point could be obtained by multiplying output voltage resulted from measurement by this number. Sensors were placed on the fixture with certain distances (225, 250, 275, and 295 cm) from the diaphragm, and the test was done on each three Mylar plates with thickness 0.1, 0.2, and 0.3 mm at each distance. Sensors No.1 and No.2 were placed at the same radius distance, and sensor No.3 was placed at less distance from radius (Figure 12).

In order to examine the repeatability of device performance and reliability of the results, some tests were repeated, and some of the tests which were not reliable due to human error or problems like non-ideal thickness of diaphragm were excluded from the analysis. Finally, 12 correct tests were selected according to Table 2 and were analyzed.

With regards to the obtained results, the last two columns of this table were related to each other by using Matlab software.

The curve shown in the Figure 13 relates optical sensor voltage values to piezoresistive sensor pressure values, such that shock wave pressure can be obtained by having synthesized sensor voltage value and using this curve. The equation of this curve is as follows:

$$P = \frac{\alpha_1 \times V^4 + \alpha_2 \times V^3 + \alpha_3 \times V^2 + \alpha_4 \times V + \alpha_5}{V^2 + (\beta_1 \times V) + \beta_2} \quad (1)$$

In this equation, V is the voltage of the optical sensor, P is the pressure that piezoresistive sensor measures, which is shock wave pressure, α and β are constants where the value of the equation is obtained by putting their values.

$$P = \frac{96.92V^4 - 36.46V^3 + 8.534V^2 - 0.9409V + 0.0374}{V^2 - 0.2172V + 0.0125} \quad (2)$$

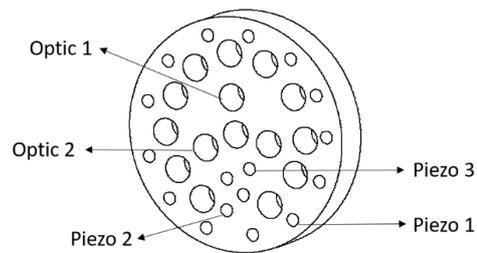


Figure 12. The location of the sensors on the fixture

TABLE 2. Results of experiments

No.	Diaphragm thickness (mm)	Distance (cm)	Driver pressure (MPa)	Piezoresistive sensor output voltage	Optic sensor output voltage	Pressure (MPa)
1	0.1	225	5.5	0.965	0.09	1.33
2	0.2	225	11	4.19	0.17	5.778
3	0.3	225	13	5.385	0.265	7.425
4	0.1	250	6	1.655	0.1	2.282
5	0.2	250	12.5	4.045	0.125	5.578
6	0.3	250	13	5.55	0.283	7.653
7	0.1	275	7.5	1.345	0.086	1.854
8	0.2	275	12	3.93	0.123	5.419
9	0.3	275	13	5.04	0.251	6.95
10	0.1	295	6	1.32	0.085	1.82
11	0.2	295	12	4.14	0.154	5.709
12	0.3	295	13.5	4.97	0.247	6.853

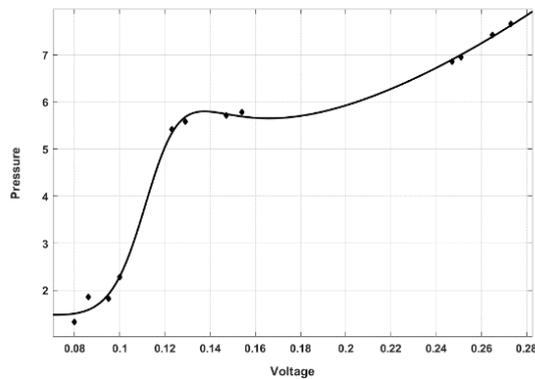


Figure 13. Converting optical sensor voltage to shock wave pressure

4. CONCLUSION

A new measurement system developed with a data acquisition method showed a shock wave diagram along with its negative part with high precision. There was no delay in showing response by the sensor after receiving the wave, and this system acted very well in measuring shock wave velocity, moving objects velocity, and in examining shock wave uniformity.

The conversion function of the output voltage to pressure was required to measure the pressure. Figure 15 and equation 2 were extracted by calibration using the cold diaphragm shock tube through 12 tests, which were performed with the piezoresistive sensor.

It is possible to obtain a repeatable output at specified conditions using designed sensors and the innovative method of data acquisition. The repeatability of the measuring system indicates the correct performance of the sensor. By calibrating this sensor, the method of converting output results to pressure diagrams was extracted.

This developed system, due to industrial production with lower cost, more comfortable operation, and more capabilities, can be used instead of piezoresistive sensors.

5. REFERENCES

- Laijun, Y., Long, Z., Xu, Z., Yong, C., Lihu, Z., Xinhua, Q. and Xianghong, Y., "Design of measurement and control system for shock tube based calibration installation of dynamic pressure transducer", in 2017 13th IEEE International Conference on Electronic Measurement & Instruments (ICEMI), IEEE., (2017), 313-318.
- Courtney, E., Courtney, A. and Courtney, M., "Shock tube design for high intensity blast waves for laboratory testing of armor and combat materiel", *Defence Technology*, Vol. 10, No. 2, (2014), 245-250.
- Davis, W.C., Salyer, T.R., Jackson, S. and Aslam, T.D., "Explosive-driven shock waves in argon", in Proceedings of the 13th International Detonation Symposium., (2006), 1035-1044.
- Duff, R.E. and Blackwell, A.N., "Explosive driven shock tubes", *Review of Scientific Instruments*, Vol. 37, No. 5, (1966), 579-586.
- Stewart, J.B., "Influence of explosively driven shock tube configuration on the mid-field blast environment", in AIP Conference Proceedings, AIP Publishing LLC. Vol. 1979, (2018), 160026.
- Stotz, I., Lamanna, G., Hettrich, H., Weigand, B. and Steelant, J., "Design of a double diaphragm shock tube for fluid disintegration studies", *Review of Scientific Instruments*, Vol. 79, No. 12, (2008), 125106.
- Andreotti, R., Colombo, M., Guardone, A., Martinelli, P., Riganti, G. and di Prisco, M., "Performance of a shock tube facility for impact response of structures", *International Journal of Non-Linear Mechanics*, Vol. 72, (2015), 53-66.
- Proulx, T., "Dynamic behavior of materials, volume 1: Proceedings of the 2010 annual conference on experimental and applied mechanics, Springer Science & Business Media, Vol. 1, (2011).
- Neupane, S., Barnes, F., Barak, S., Ninnemann, E., Loparo, Z., Masunov, A.m.E. and Vasu, S.S., "Shock tube/laser absorption and kinetic modeling study of triethyl phosphate combustion", *The Journal of Physical Chemistry A*, Vol. 122, No. 15, (2018), 3829-3836.
- Payne, D., Flaherty, S.P., Barry, M.F. and Matthews, C.D., "Preliminary observations on polar body extrusion and pronuclear formation in human oocytes using time-lapse video cinematography", *Human reproduction (Oxford, England)*, Vol. 12, No. 3, (1997), 532-541.
- Boyce, R., Pulford, D., Houwing, A. and Mundt, C., "Rotational and vibrational temperature measurements using cars in a hypervelocity shock layer flow and comparisons with cfd calculations", *Shock Waves*, Vol. 6, No. 1, (1996), 41-51.
- Thethy, B., Rezay Haghdoost, M., Oberleithner, K., Honnery, D. and Edgington-Mitchell, D., "Influence of nozzle geometry on detonation-driven and shock-driven transient supersonic jet flow", in 24th International Society for Air Breathing Engines Conference., (2019), 1-22.
- Medhi, B., Hegde, G.M. and Reddy, K.J., "Time-resolved quantitative visualization of complex flow field emitted from an open ended shock tube using a wavefront measuring camera", *Optics and Lasers in Engineering*, Vol. 122, (2019), 354-360.
- Nativel, D., Niegemann, P., Herzler, J., Fikri, M. and Schulz, C., "A study of ethanol oxidation in high-pressure shock tube: Ignition delay time measurements and high-speed imaging of the ignition process", International Colloquium on the Dynamics of Explosion and Reactive Systems, Beijing, China, (2019).
- Keys, D.A., "Lvi. A piezoelectric method of measuring explosion pressures", *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Vol. 42, No. 250, (1921), 473-488.
- Oliver, M., Spooncer, R. and Ghezelayagh, M., "An autoreferenced two-state optical fibre reflective sensor", in Fibre Optics' 86, International Society for Optics and Photonics. Vol. 630, (1986), 233-238.

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این مقاله به معرفی یک سیستم اندازه‌گیری نوری مشخصه‌های موج شوک پرداخته است. این سیستم با روشی مبتکرانه با قراردادن یک صفحه فلزی متصل به فنر در مقابل جبهه موج شوک و آب بندی آن، با اندازه‌گیری جابجایی آن در هنگام برخورد صفحه موج شوک، با کمک تابش و تغییر میزان بازتابش نور، توانسته است با تبدیل این داده‌های نوری به ولتاژ، نمودار فشار موج شوک را ترسیم نماید. این سیستم در آزمایش تجربی انجام شده، هیچ تاخیری در زمان عکس العمل برخورد موج نداشته و در این مقاله توضیح داده شده است که با کمک فیکسچر طراحی و ساخته شده، چگونه با این سیستم میتوان علاوه بر سرعت موج شوک، سرعت اجسام متحرک را نیز اندازه‌گیری نمود و همچنین صفحه‌ای شدن موج شوک را بررسی کرد؛ بعد از آن کالیبراسیون با کمک یک سنسور معیار پیزورزیستیو در یک لوله شوک دیافراگمی سرد، با فشار ۵/۵ تا ۱۲/۵ بار با انجام ۱۲ تست صورت گرفته و در نهایت روش اندازه‌گیری مقدار فشار مثبت و منفی موج شوک بوسیله‌ی سنسور ساخته شده و نمودار و رابطه آن نیز تبیین شده است.

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