Journal of Scientific & Industrial Research
Vol. 70, September 2011, pp. 762-766

Small caliber projectile velocity measurement system based on a single laser source and a single detector

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Received 14 January 2011; revised 24 July 2011; accepted 04 August 2011

This study presents development of an inexpensive modular system based on the measurement of time of flight (ToF) of a projectile between two parallel laser screens for velocity measurement of small caliber projectiles and can be used for both indoor and outdoor ranges. System design consists of a single source (laser diode) and a single detector is used to construct two screens. It also provides better velocity measurement accuracy because both screens are generated from same source and have same sensitivity. Velocity measurement accuracy of system is better than 0.08%. A 100 MHz digital oscilloscope is used to measure ToF, which provides 20 ns time base accuracy.

Keywords: Data acquisition & processing unit, Digital storage oscilloscope, Knife edge scanning technique, Projectile velocity, Small caliber projectile, Speed measurement, Time of flight (ToF)

Introduction

Time of flight (ToF) measurement technique is widely used for measurement of velocity of projectile (VoP). For large projectiles, Doppler frequency shift measurement technique is also used for measurement of VoPs, but for small projectiles, this technique has limitations. Based on visible and infrared (IR) radiations, many instruments[1-10] are reported as optical screen based systems that provide high resolution and sensitivity, and are free from EMI / EMC effects. Screens of existing systems use either visible or IR sources (single or multiple), and refractive or reflective optics. A laser and prism based system with large size screens has also been reported[9]. All reported systems are complex and expensive as they incorporate two screens, which have been constructed using a minimum of two sources and two detectors for measurement of VoPs. Apparatus employing sun light for construction of screens[6] cannot be used for indoor ranges and also the accuracy of such an apparatus is very much dependent on intensity of sunlight, which does not remain constant.

This study presents a laser based modular system design using a single source and a single detector for construction of two similar optical screens for velocity (1-1000 m/s) measurement of small caliber projectiles.

Experimental Section

Design and Description of System

The designed system consists of a source module, an optical module, a detection unit and a data acquisition and processing unit (Fig. 1a). Two similar screens (Screen 1 & Screen 2) were constructed using only one source and one detector. The system design is based on 5 mm minimum size of projectile and maximum velocity of 1000 m/s. Source module (Fig. 1b) consist of a laser diode[11] (670 nm, 3 mW, 0.3 mrad divergence; temp., 10-60°C; and beam size, 4 mm x 2 mm), a beam expander and a collimator (10 X) and a slit (40 mm x 0.5 mm). Optical module comprises of two similar plane mirrors (size, 50 mm x 10 mm; surface accuracy, $\lambda/2$). Detection unit[12] includes a slit (40 mm x 0.5 mm), a lens (focal length, 350 mm), a detector (responsivity at 670 nm, 0.4 A/W; rise time, 12 ns; temp., - 40-60°C; and active area, 2.5 mm diam) and a digital storage oscilloscope (100 MHz, compatible with laptop). Data acquisition & processing unit is a laptop (Core 2 Duo processor, Windows XP, 4GB RAM, 320 GB HDD). Slit1 is fitted in collimator assembly in front of exit lens and slit2 is fitted in front of collector lens assembly, which consists

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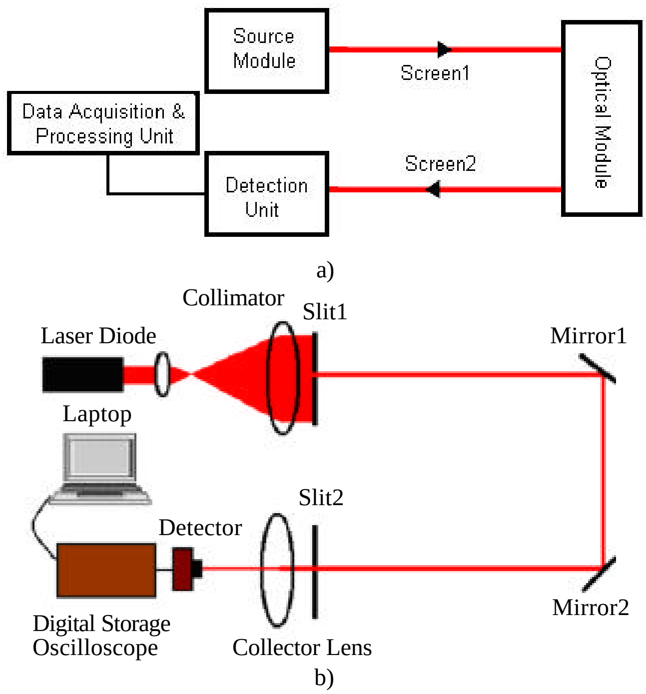

Fig. 1 — System: a) block diagram; b) configuration (top view)

of a collector lens and a detector. Laser collimator assembly and collector lens assembly are mounted in separate uprights (with provision of movement in vertical axis). Both mirrors are mounted in separate uprights, each equipped with two tilts (at the back of mirror mount), vertical movement and rotation (in horizontal plane) provisions for accurate alignment of collimated beam. All uprights are mounted rigidly on a metal plate, which has thread holes for mounting uprights on the plate using clamps. Laser is collimated by adjusting the lens fitted in laser housing, using spanner wrench and height gauze (resolution, 0.01 mm), to measure the size of collimated laser beam. After adjustment, size of collimated beam was 4 mm near laser and 4.5 mm at a distance of 1.5 m (which is more than the total path length of beam in the set up). Laser upright is rigidly fitted at one end of the table. Collimator assembly is mounted in front of the laser mount maintaining a distance of 20 mm between front end of laser and entrance lens of collimator. Central heights of laser and collimator assembly are matched using vertical movement provision. Collimation property of output beam of collimator is checked. Size of collimated beam was 40 mm near collimator and 40.05 mm at a distance of 1.5 m.

Mirror1 upright is mounted on table top keeping a distance of 480 mm between slit1 and mirror1. Mirror1 is aligned (using tilt screws) so that collimated beam from slit1 falls normally on mirror1. To do this, surface of

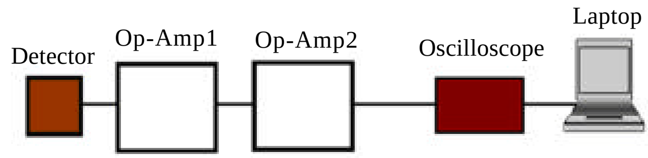

Fig. 2 —Electronic circuit

mirror1 is made parallel to slit1. In such situation, incident beam falling on mirror1 is reflected back towards slit1. For accurate alignment of mirror1 with slit1, reflected beam is made to pass through slit1 using tilt screws. After this, mirror1 is rotated by 45°. Mirror2 is kept at a distance of 450 mm from mirror1 and aligned with slit1. Mirror2 is aligned by rotating about its vertical axis so that incident beams incidents on it at 45°. Detector assembly is also mounted on the table, keeping a distance of 480 mm between slit2 and mirror2. Height of detector assembly is adjusted so that reflected beam from mirror2 passes through slit2 and finally focused on detector by collector lens. Using a knife edge scanning technique, a bench set up is used to measure screen separation distance. Bench is equipped with upright, which provides a scale of 500 mm and a vernier scale for measurement of distance along the length of bench with a resolution of 0.01 mm. Upright also has a provision of movement along the width (horizontal movement) of bench. A knife (length, 40 mm) is mounted vertically on upright. Bench set up is placed near slits and knife edge is moved across the width of beam passing through slit1. Output voltage of detector is recorded (using oscilloscope) when knife edge is kept just outside the beam, then it is moved across the beam using horizontal movement till output voltage dropped to 89.9% of full signal and position of upright is recorded (say reading 1). A similar experiment is performed with beam near slit2 and upright position is recorded (say reading 2). Difference between two readings is called screen separation distance. Similar measurements are done in the middle of width of active zone of screens and near mirrors. Average value of three measurements was 450 mm and maximum variation in the measurements along width of active area of screens was 0.07 mm. Using maximum screen separation error (0.07 mm) and width of active area of screens (480 mm), the parallelism error (0.5 min) was estimated.

Width of slit depends upon minimum size of projectile to be measured and responsivity of detector. For measuring ToF of a projectile, it is fired normally to active areas of screens and two triggering pulses are generated when it crosses screens. Time duration between triggering pulses represents ToF, measured by oscilloscope. For measurement of VoP of a high speed projectile, a very narrow slit introduces more noise in output signal, which effects repeatability of measurement, and a wider slit introduces more uncertainty in ToF measurement due to large variation in triggering positions along the width of both screens. With these aspects, 0.5 mm slit width provides best performance of the system with minimum error.

During measurement, interruption of screen by projectile produces a change in output current of detector, which is used in photoconduction mode with reverse bias[14]. High speed operational amplifiers [Op-Amp1 LM 318) & Op-Amp2 (LM 318)] are used to amplify signal so that screens are very sensitive even for the smallest caliber projectile (Fig. 2). Op-Amp1 converts detector output current into voltage and Op-Amp2 amplifies signal by a factor of 2. High speed amplifiers in the circuit increases noise exponentially in output signal as VoP increases, whereas signal amplitude decreases, reducing signal to noise ratio (S/N). Amplifier and signal conditioning circuits[14] are designed to minimize noise. Output signal from Op-Amp2 is transferred to oscilloscope. During measurement, on interruption of screens by projectile, two triggering pulses are generated, then recorded and displayed by oscilloscope. Display data of oscilloscope is transferred to laptop for analysis and computation of velocity.

Operation

In a display of the measurement records (Fig. 3), vertical and horizontal scales represent voltage and time respectively. Time is set in the scale of 1 ms/div to 50 µs/div, depending upon VoP. In order to record ToF of projectile, horizontal cursor is set below the signal output voltage at 89.9% of the full signal to avoid false triggering. Horizontal cursor position decides triggering voltage level of screens. If triggering voltage is small, the system shows satisfactory performance even in the case of a small caliber projectile with high velocity. To measure VoP, projectile is fired perpendicular to the screens. When it crosses Screen1, a triggering pulse is generated (Fig. 3). Interruption of screen by projectile produces a decrease in intensity falling on detector, which introduces a corresponding fall in output signal. A similar phenomenon occurs when it crosses Screen2. Two triggering pulses are generated. Display data is transferred to laptop. ToF is measured by measuring time between two pulses and velocity is computed using ToF and screen separation distance. The system can measure VoPs (minimum size, 5 mm) and velocity (1-1000 m/s), and can be used in indoor and outdoor ranges. In both ranges, the system

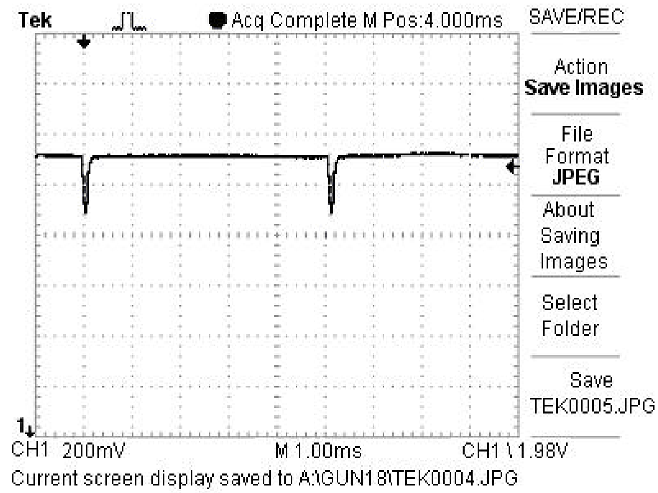

Fig. 3—Oscilloscope-time measurement result

provides velocity measurement results with specified accuracy. Limits of minimum size of projectile and velocity range are set keeping in view the specifications of optical, mechanical, electronic components and electronic circuitry and desired errors involved.

Error Analysis

Measurement accuracy of velocity depends upon screen separation distance measurement error and ToF measurement error of the smallest projectile with highest velocity. The present system is designed for 5 mm smallest size of projectile and 1000 m/s highest VoP. VoP is defined as $v = s / t$, and relative error in velocity is represented as $dv / v = ds / s + dt / t$, where v = VoP, s = screen separation distance, t = ToF, dv = velocity measurement error, ds = screen distance measurement error, and dt = time of flight measurement error. Both ds and dt depend upon the accuracy of components/modules and alignment error of optical modules.

Error Estimation

Distance between the two screens is kept at 450 mm and measured using bench set up within an accuracy of 0.01 mm (verify using knife edge scanning technique). Parallelism error between the screens is of the order of half a minute which produces 0.07 mm error in the screen distance (verify using knife edge scanning technique). Though two screens are constructed from same source, there is variation in widths of two screens due to divergence in collimated beam and also variation, which can produce variation in the sensitivity of two screens. A maximum error (0.1 mm) in screen distance can be introduced due to different triggering positions along the width of screens. To verify this error, a thin blade is mounted on upright with provision of a linear movement. Upright is placed near screen1 and blade is moved across the beam (along width of beam). Output of detector is fed to oscilloscope. Vertical cursor on the screen of oscilloscope is placed at 89.9% of output voltage of detector and horizontal cursor is placed anywhere on the screen near the right side. A number of experiments are carried out by moving the blade along the width of beam and positions of blade are recorded from the vernier provided with upright, when triggering pulses are generated on interruption of the beam. Similar experiments are performed for screen2. It was notice that maximum difference between triggering positions along both the screens was 0.1 mm. Triggering variation can introduce ds (0.1 mm), which can be generated because the widths, intensities and illumination uniformities of two screens are not same. Combined effect of these aspects can produce an error of 0.18 mm. The dt (0.2 µs) is inclusive of oscilloscope error, temporal circuit noise, and measurement error due to recording of reading from oscilloscope.

For justification of these errors, several experiments are performed. A time base accuracy of oscilloscope is 20 ns, reported by the manufacture. Temporal circuit noise can be of the order of 80 ns. Circuit noise will be maximum in case of a projectile with the smallest size and moving with the highest velocity of 1000 m/s. Theoretically, such type of projectile will pass through the screen (width, - 0.5 mm) in 500 ns. To validate estimation of circuit noise, a 500 ns TTL pulse is generated by a pulse generator. It is passed through the developed circuit and output is measured using oscilloscope. Width of output pulse changes due to circuit noise. The same experiment is repeated a number of times and widths of output pulses are recorded at a level of 89.9% of full signal (% level of output is same, which is used during velocity measurement). Maximum variation in the width of output pulses in comparison to the input pulse was found of the order of 80 ns.

For estimating of dt due to recording from oscilloscope (which will be maximum in case of fast projectile), horizontal time scale is kept at 50 µs/div (each division is further divided into 5 small divisions) scale. After performing the experiment, ToF is recorded by changing time scale from 50 µs/div to 500 ns/ div (one small division corresponds to 100 ns). Maximum error of the order of 100 ns was recorded in measurement of ToF due to recording of reading from oscilloscope. Taking into consideration of ds and dt, dv is 0.08%.

Results and Discussion

System Performance

Performance of present system was evaluated with 40 mm height of each screen and 450 mm screen distance. A number of experiments were conducted with slow and high VoPs of different calibers. To view the system performance in indoor and outdoor ranges, a number of test trials were carried out.

Test Trial 1 (Indoor Range)

A number of test trials were performed in indoor lab using low and high VoPs in 30 lux ambient light conditions. Low VoPs like steel balls thrown by humans with different muscular power, 0.22-in. pellet fired by air gun and high VoP fired by rigidly mounted INSAS gun (placed at 7 m from the system) were tested. Test results of different projectile types showed following velocities: 5.56 mm bullet fired by rigidly mounted INSAS rifle (887± 9 m/s), 895.2; 0.22-in. pallet fired by hand-held air gun, 82.4; and 5 mm steel ball thrown by humans with different muscular power, 4.7, 9.1 & 13.6 m/s. Velocity data for INSAS rifle was provided by manufacturer. Test results show that present system is useful for measurement of both low and high VoPs.

Test Trial 2 (Outdoor Range)

To evaluate the system performance in very bright light conditions of the order of 10^5 lux, the system was tested in outdoor range (ambient temp., 42°C). The system was installed on a table and a cover with a slit of 1 mm was placed on detection unit to avoid ambient light entering in active area of detector. Guns were rigidly mounted on a heavy metal table placed at a distance of 7 m from the system. Bullets with different calibers and velocities were fired from different guns (INSAS rifle, SLR, AK-47 rifle and SMC). Test results of different projectile types showed following velocities (Velocity data in parentheses were provided by manufacturers): 5.56 mm INSAS rifle (887±10 m/s), 895.2, 885.6, 881.5 & 878.3; 7.62 mm SLR (817±9 m/s), 810.1, 817.7, 824.2 & 814.5; 7.62 mm AK-47 rifle (720± 10 m/s), 714.9, 728.3, 710.1 & 719.5; and 9 mm SMC (397±15 m/s), 390.3, 410.1, 405.4 & 386.8 m/s. Test results are within velocity ranges supplied by manufacturers, which confirm the satisfactory performance of the system for high VoPs at outdoor ranges.

Thus in the present system, both screens, generated from same source, provide similar sensitivity, which ensures better performance as compared to the screens used in existing optics based instruments/apparatus. Projectile velocity is computed using ToF recorded by 100 MHz storage oscilloscope and distance between two screens. System design is modular and distance between screens can be changed easily. It does not require any expensive aspheric optical components (parabolas, cylindrical lenses etc.). System design is innovative, cost-effective and modular in nature and is able to measure velocity (accuracy, 0.08%) over a wide range of VoPs. The system can be easily used for both indoor and outdoor ranges. The system also ensures good performance over a wide range of temperature and ambient light conditions and other environment conditions like high ballistic pressure and shock waves generated during the measurement of high speed projectiles. Trial results in a wide range of ambient light conditions in both indoor and outdoor ranges indicate that system performance is consistent in both indoor and outdoor ranges.

Conclusions

Basic advantage of present system over existing systems is that its design is innovative, and cost-effective because of screens construction technique. Only one source and one detector are employed to develop two screens. Sensitivity of both the screens are similar because of the design aspect, which in turn produces better projectile velocity measurement accuracy. The system design is modular in nature so screen distance can be increased or decreased easily. Also, the system can be used for both indoor and outdoor ranges.

Acknowledgements

Authors thank TBRL, Chandigarh for providing funds & test trial facility for this project. Authors are also grateful to Dr Pawan Kapur, Director, CSIO, Chandigarh; Dr Satish Kumar, Director, TBRL; and Dr N S Mehla, Scientist, CSIO; for their valuable guidance and encouragement for publishing this paper. Thanks are also due to Mr Ravneet Singh and Mr Amit Dandyan, Project Assistants, CSIO for providing assistance in the system development, and Mr Vikas Bhardwaj and Mr Rajiv Kumar, Scientists, TBRL for conducting field trials.

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