AN OPTOELECTRONIC SYSTEM THAT MEASURES THE LINEAR SPEED OF MOVING OBJECTS

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ABSTRACT

In this study, an optoelectronic system which measures the linear speed of moving objects (such as a bullet) has been considered. The optical scheme of the system has been examined. The optical scheme of the transmitter that forms homogeneous light ray in the scope area and the method used in choosing the optimum distance between the light rays have been given. This distance has been taken as half length of the detected object and analysis of the system has been made. The effects of the distance between sensors and the length of the scope area to the error occurred have been found. Error graphics and equations have also been given. Using the analysis, a microprocessor system that measures the bullet speed has been designed.

I. INTRODUCTION

Speed of the moving objects can be measured with optoelectronic methods. One of the advantages of these methods is the ability to determine the object speed without any contact. The other one is that sensors which have been designed with optoelectronic methods can change their state quickly.

The fundamental of this method is to measure the time spent by the object between two sensors. The block diagram of the system is shown in Figure 1.

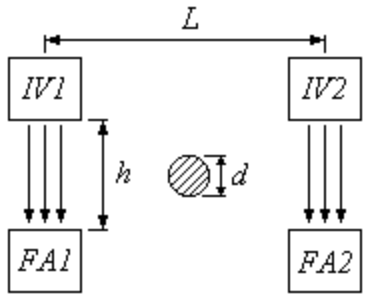

Figure 1. Block diagram of the speed measuring system

System consists of two sensors. Each sensor is formed by a LED-photodetector pair which are optically connected. First sensor includes IV1 transmitter and FA1 receiver. The second sensor includes IV2 transmitter and FA2 receiver. The distance between the transmitter and the receiver is indicated by *L*.

The linear moving object (bullet) comes to the first sensor's scope area and while passing, it cuts the rays of this sensor. Then it comes to the second sensor's scope area and cuts the rays of the second sensor. Measuring the object's passing time between sensors and using the following equation,

$$V = \frac{L}{t_o} \quad (m/s) \tag{1}$$

where t_o is the passing time of the object, the speed of the object can be determined.

II. ANALYSIS OF OPTOELECTRONIC SPEED MEASURING SYSTEM

The purpose of this analysis is to determine sensor dimensions (the scope area), the distance between sensor rays and the time constant of the photodetector. Let's make some assumptions to simplify calculations.

1. Sensor rays are parallel to each other,
2. Object has a spherical shape with diameter *d*,
3. Propagation of light rays between transmitter and photodetector is linear and homogenous,
4. Maximums of transmitter and photodetector spectrums are the same,
5. Light rays emitted by transmitters are sufficient for required operations,
6. Rise and fall times of photodetector current are equal.

Let's consider the structure shown in Figure 2 for performing the analysis, where *M* is the bullet, *a* is both the distance between light rays and photodetector width, *m* is the width of photodetector array.

For the rays to be homogeneous in scope area, maximum value of the distance *a* must be equal to the radius of the object *M*, as shown in the following equation.

$$a = \frac{d}{2} \tag{2}$$

If photodetectors that form the photodetector array have the same properties, one can say $I_{F1}=I_{F2}=....=I_{FN-1}=I_{FN}=I_F$ for currents of photodetectors. In this case, the total photocurrent obtained when the object passes between two adjacent photodetectors will be, LASER

$$(I_{FN-1}/2)+(I_{FN}/2)=I_F \tag{3}$$

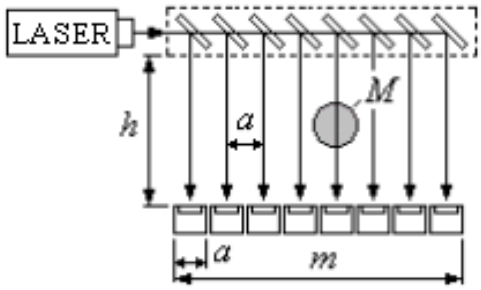

Figure 2. Sensor Structure

The area scanned with parallel light rays between transmitter and photodetector forms the scope area. If *h* and *m* values are known, the scope area can be defined as

$$A = h \times m \ \ (cm^2) \tag{4}$$

where $m = N \times a$. To simplify calculations, the distance between the light rays and the width of light sensitive surfaces of photodetectors is assumed to be equal. To form homogeneous light rays in the scope area, continually placed semi-permeable glasses has been used in fototransmitter structure.

Following equation can be used to determine rise and fall times of the photodetector used in the system

$$t_m = \frac{d}{V_{\max}} \tag{5}$$

where $V_{\max}$ is the maximum speed of bullet and *d* is the length of the bullet. For example, the maximum speed of the pneumatic gun bullet is between 160m/s and 190m/s. If we take $V_{\max}=170m/s$ and $d=3mm$, the time spent by bullet under the light rays can be calculated as

$$t_m = \frac{0.003m}{170m/s} = 0.018ms$$

Assuming that rise and fall times of photodetector are equal ($t_r=t_f=t_p$), time constant of the photodetector will be

$$\tau_p = t_p = 3t_m = 3 \cdot 0.018ms = 54\mu s \tag{6}$$

The diagram shown in Figure 3 can be used in choosing the optimum optical scheme of the measuring system.

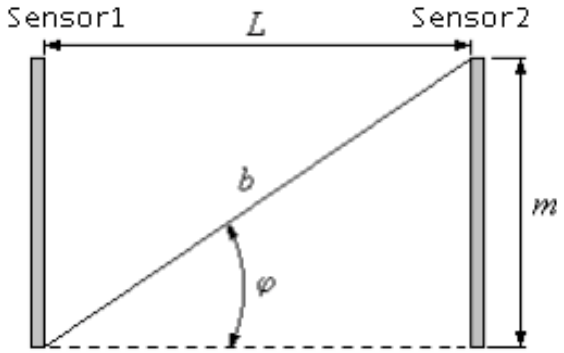

Figure 3. Simplified scheme of the measuring system.

If the bullet makes an angle φ with the ground, the distance taken by the bullet will be

$$L_D = b = \frac{L}{\cos\varphi} \tag{7}$$

In this case, bullet takes L_D distance instead of *L* distance and the error occurred will be

$$\delta = \frac{L(\cos\varphi - 1)}{L\cos\varphi} \cdot 100 = \frac{\cos(\arctan m/L) - 1}{\cos(\arctan m/L)} \cdot 100 \tag{8}$$

It is obvious from (8) that the error depends on *m* and *L* values. Error variations with *m* and *L* values are shown in Figure 4 and Figure 5.

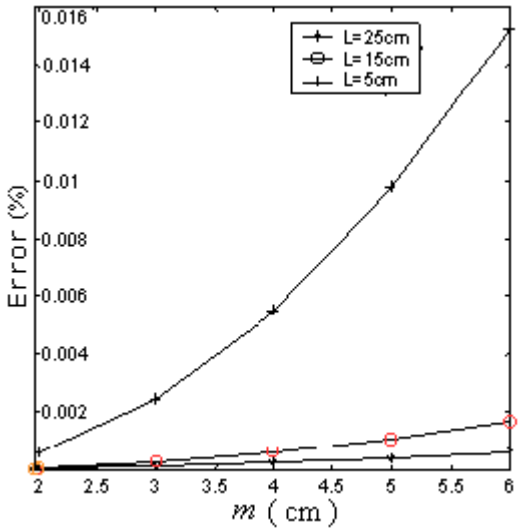

Figure 4. Error variation with *m*.

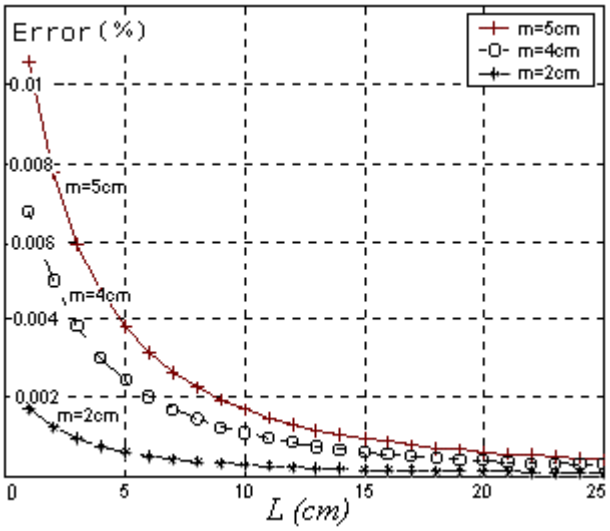

Figure 5. Error variation with L.

As it is shown in Figures 4 and 5, error can be decreased by decreasing m or increasing L. To find the effect of these values to the error, lets take partial derivative of the equation (8) with respect to m and L.

$$\frac{\partial \delta}{\partial m} = -\frac{L}{L^2+m^2}\frac{\sin(\arctan m/L)}{\cos^2(\arctan m/L)} \tag{9}$$

$$\frac{\partial \delta}{\partial L} = \frac{mL}{L^2+m^2}\frac{\sin(\arctan m/L)}{\cos^2(\arctan m/L)} \tag{10}$$

Assuming $\frac{\partial \delta}{\partial m} = 0$ and $\frac{\partial \delta}{\partial m} = 0$, the extreme points of the graphics, i.e. the m and L values that make the error maximum or minimum, can be found.

$$\frac{\partial \delta}{\partial m} = 0 \quad \frac{\partial \delta}{\partial L} = 0$$
$$\Rightarrow \sin(\arctan m/L) = 0$$
$$\Rightarrow \arctan m/L = k\pi$$
$$\Rightarrow \tan k\pi = \frac{m}{L} = 0 \qquad \Rightarrow m{=}0$$

$$\frac{\partial \delta}{\partial L} = 0$$
$$\Rightarrow \sin(\arctan m/L) = 0$$
$$\Rightarrow \arctan m/L = k\pi$$
$$\Rightarrow \tan k\pi = \frac{m}{L} = 0 \qquad \Rightarrow L{=}\infty$$

If $\left.\frac{\partial^2 \delta}{\partial m^2}\right|_{m_0} > 0$, m_0 is the minimum point of the error graph and has the value that makes the error minimum. If $\left.\frac{\partial^2 \delta}{\partial m^2}\right|_{m_0} < 0$, m_0 is the maximum point of the graph and has the value that makes the error maximum.

As it is seen in Figure 5, error has a minimum point at $L{=}\infty$.

III. SYSTEM CONFIGURATION

Using the analysis given above, a system that measures the bulled speed has been designed. The block diagram of the system is shown in Figure 6.

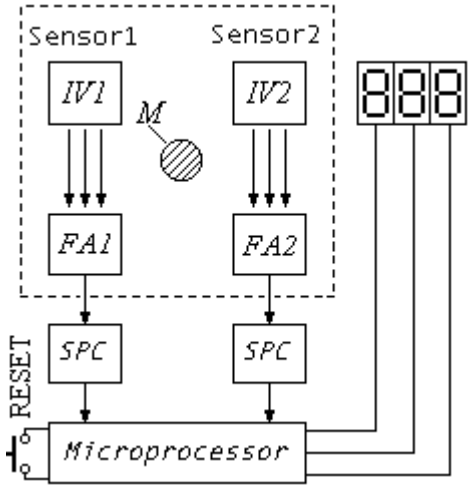

Figure 6. Block diagram of the bulled speed measuring system.

System consists of two sensors. The distance between the sensors and the width of scope area have been taken as L=25cm and m=5cm, respectively.

Having cut the first sensor rays and having taken the distance L in a time period t_o, the bullet cuts the rays of the second sensor. Signals obtained from photodetector outputs pass through the SPCs (Signal Processing Circuits) and come to the microprocessor's input. These signals and related time diagrams that are obtained from photodetector outputs are shown in Figure 7.

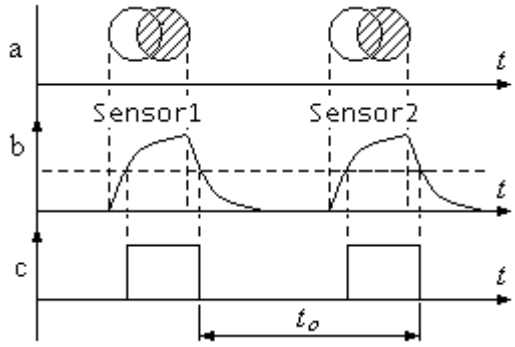

Figure 7. Signals and related time diagrams that are obtained from photodetectors outputs.

To prevent system delays, the measured time is taken from rising edges or falling edges of the pulses. In Figure 7, the measured time is taken from the falling edges of the pulses.

Microprocessor calculates the bullet speed and shows the measured value on the display. After every shooting, system is prepared for new shooting by pressing the 'reset' button.

IV. RESULTS

Optical scheme of the optoelectronic system that measures the bullet speed has been built up. Provisions for system design has been given. The analysis of the system has been made. The effect of the distance between sensors and the length of the scope area to the error occurred have been examined and the extreme points have been found. Determination of the photodetector time constant used in the system has been shown. Using the analysis given, a microprocessor based optoelectronic system has been designed and one hundred shootings have been made. The results are given in Table 1.

After one hundred shootings, the average value of bullet speed has been found as 180m/s. Standard deviation is 5.74. The distribution of results given in Figure 8 has been obtained with SPSS program and shows a normal distribution. That is, measured values are mathematically correct.

REFERENCES

1. E. Musayev, "Optoelectronic Circuits and Systems", Birsen Press, Istanbul, 1999 (in Turkish).

Shooting	Speed(m/s)	Shooting	Speed(m/s)	Shooting	Speed(m/s)	Shooting	Speed(m/s)	Shooting	Speed(m/s)
1	189	**21**	182	**41**	186	**61**	190	**81**	181
2	188	**22**	182	**42**	185	**62**	179	**82**	177
3	182	**23**	185	**43**	179	**63**	172	**83**	181
4	188	**24**	176	**44**	179	**64**	177	**84**	176
5	180	**25**	170	**45**	173	**65**	180	**85**	189
6	169	**26**	185	**46**	188	**66**	182	**86**	178
7	176	**27**	179	**47**	182	**67**	189	**87**	182
8	189	**28**	178	**48**	176	**68**	172	**88**	168
9	173	**29**	177	**49**	176	**69**	186	**89**	189
10	180	**30**	172	**50**	181	**70**	188	**90**	176
11	179	**31**	177	**51**	176	**71**	180	**91**	170
12	173	**32**	180	**52**	189	**72**	172	**92**	181
13	188	**33**	176	**53**	179	**73**	177	**93**	176
14	180	**34**	170	**54**	173	**74**	179	**94**	177
15	182	**35**	185	**55**	179	**75**	172	**95**	181
16	188	**36**	176	**56**	186	**76**	189	**96**	191
17	185	**37**	181	**57**	184	**77**	180	**97**	185
18	188	**38**	185	**58**	173	**78**	171	**98**	185
19	176	**39**	179	**59**	175	**79**	180	**99**	189
20	175	**40**	183	**60**	179	**80**	173	**100**	175

Table 1. Shooting results.