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EXPERIMENTAL INVESTIGATION OF PERFORMANCE OF A MINIATURE SCHLIEREN SYSTEM FOR USE IN A SHOCK TUBE*

By Matsunosuke IWASAKI** and Mitsushi OHKURA***

Abstract

Contribution of the components of a miniature schlieren system to its performance is investigated and design data are obtained. It is shown that the careful adjustment and selection of the components of the system can produce sufficient output pulses to perform the reliable measurement of shock velocity up to a shock Mach number of 2.6, which corresponds to about 2.5 mm Hg in the low pressure chamber and 1 ata in the high pressure chamber.

1. Introduction

Shock tubes have been used in investigations of the flow around bodies, the development of boundary layers, the chemical reactions in high temperature, etc. They also are used as the driving unit of a hypersonic shock tube. In these experiments, it is essential to know the Mach number of hot gas behind a shock wave. This value is obtained by substituting the shock Mach number, viz. $M_s = U/a$ which is obtained from the measured shock velocity U divided by the sound velocity a at room temperature for the theoretical equations of normal shock wave. Accordingly, the accurate measurement of shock velocity is indispensable for the experiment with a shock tube.

There are many reports[1,2,3,4] of the method for measurements of shock velocity. Among these the authors have used the same method as Geiger and Mautz.[4] In this method, a shock velocity is found by measuring the time during which a shock wave runs between two fixed points along a shock tube, by triggering an electronic counter with electric pulses from the systems which are composed of miniature schlieren systems and photomultipliers located at the two points. These systems are often called *light screens.* Hereafter we shall call these systems the *miniature schlieren systems.* They have been manufactured and adjusted with trial and error, so that its design data are very scarce. For a

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high shock Mach number, the working performance of this system becomes less reliable. For example, when the low pressure chamber is pumped out less than 10 mm Hg while the high pressure chamber is maintained at 1 ata, which corresponds to a shock Mach number $M_s \doteqdot 2.5$, the miss in measurements of shock velocity increases. To settle this trouble, the authors have investigated experimentally the effect of compornents of a special miniature schlieren system upon its performance.

2. Apparatuses

2-1. Miniature schlieren system

The miniature schlieren system is illustrated by Fig. 1. The light source F is a double wounded ribbon filament perpendcular to the page. It is the 50 watts (10 volts, 5 amperes) incandescent bulb used in a talkie projector. Its watt-age,

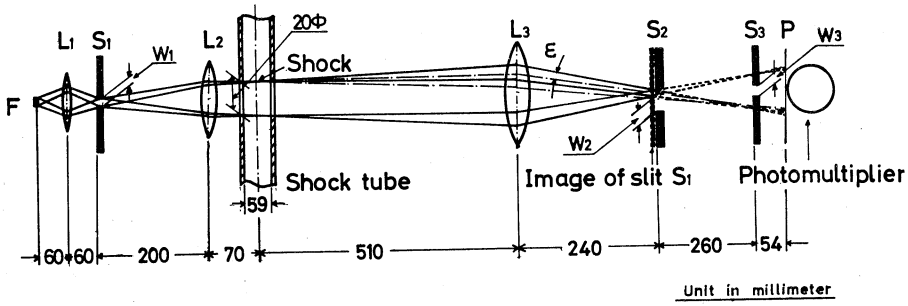
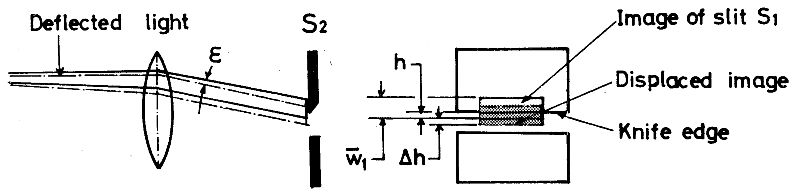
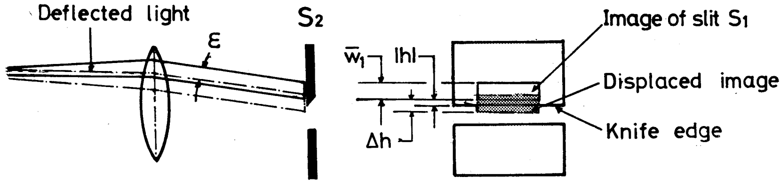


Fig. 1.



(a)



(b)

Fig. 1. Miniature schlieren system and schlieren knife edges. (a) Configulation of an ordinary knife edge. (b) Configulation of the present knife edge.

that is, the brightness was able to be varied by changing service voltage according to necessity of experiments. The bulb was lighted by the electric current which was rectificated with Tunger rectifier. To keep away from fluctuation of sixty cycles of its brightness, three alkali batteries were connected in parallel to the bulb.

The image of the light source focused by the lens L_1 was adjusted to form a image of uniform brightness on the slit S_1-plane. In this case, details of the image of the filament had to be completely extinguished. Then the effective light source considered as the practical light source of this system was the image, of apparently uniform illumination, cut out by the slit S_1 of width 1 mm and height 11 mm. The flux of light made parallel to the axis of the system by the lens L_2 passed through the test-section of the shock tube, and arrived at the schlieren lens L_3 with a long focal length. This paralleded flux was focused on the slit S_2-plane with a knife edge, so that it was the bright image of the slit S_1. The slit S_3 was located here in order to restrict the light flux into a photomultiplier and to keep the noise level and the dark current of a photomultiplier as low as possible, consequently to obtain the good signal-to-noise ratio of a photomultiplier. On the other hand, it is regulated for the system to act at the moment when a shock front arrived at the centre of the measuring window. The image of the central plane of the shock tube was composed at the position of the slit S_3. Of course, in order to obtain the real image of the test-section the distance between the lens L_3 and the test-section must be larger than the focal length of the lens L_3. The symbol P represents the plane of incidence of light on the outer surface of a phototube. The window glasses of the test-section are show-window glass, sold on usual market, whose thickness is 9 mm and the effective diameter is 20 mm.

The focal length and the aperture of the lenses used in the experiments are as followings: the lens L_1 is about 50 mm and 30 mm, the lens L_2 is about 200 mm and 40 mm, and the lens L_3 is about 240 mm and 60 mm, respectively. The lens L_1 is a magnifying glass lens on the market. The lens L_2 and L_3 are made in Shimadzu Seisakusho Co., Ltd. and each consists of one and two lenses, respectively. As any lens is no free from chromatic and spherical aberration and of astigmatism, these have not the high performance if they are considered lenses themselves. It seems, however, for these aberrations to gave no great effect on the working condition of the present system by the following reasons: as regards chromatic aberration, the spectral sensitivity band of the photomultiplier used is wide, about spherical aberration, the width of the slit S_3 is small and set at the central position of the image of the measuring window, and about astigmatism, the width of the slit S_1 is very small.

As it is necessary for the edges of the slit S_1 and S_2 to be maintained as straight as possible, the authors have used the optical slit of Shimadzu Seisakusho Co., Ltd. manufactured for the experiment of photoelasticity in stead of making them by ourselves.

2–2. Photomultipier

In following experiments, photomultipliers[5] of MS-9S and 7696 manufactured by Toshiba Co., Ltd. were used. The former was mainly used. It is said that the frequency response of these tubes is uniform as far as 100 Mc/s. The authors, however, think that this remarkable performance will be realized provided that the value of the load resistor of the anode is sufficiently small and is carefully compensated for stray capacitance and inductance.

The characteristics of spectral sensitivity are shown schematically in Fig. 2 (a)[5]. In a photomultiplier MS-9S, the upper limit of the spectral sensitivity is about 7000 Å and the maximum spectral sensitivity band is about 4000±500 Å. In a 7696, the former is about 6600 Å and the latter is about 4400±500 Å. The

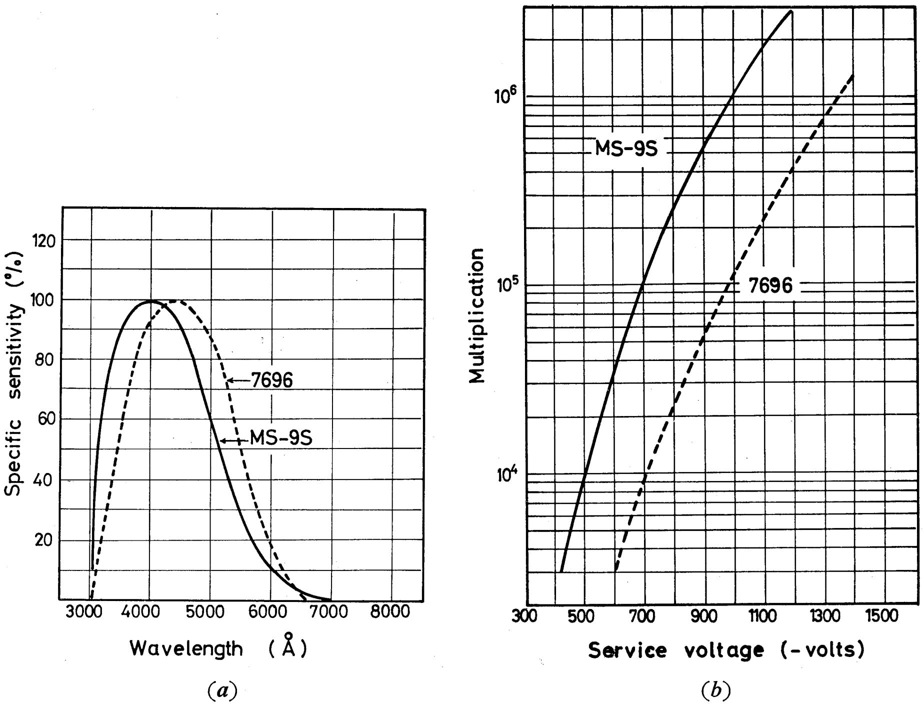


Fig. 2. Representative characteristics[5] of photomultipliers MS-9S and 7696. (*a*) Specific sensitivity. (*b*) Multiplication.

representative multiplication of MS-9S and 7696 are shown in Fig. 2 (b)[5].

The relation between incident light flux (μlm) and the corresponding output voltage (volts) from the photomultiplier MS-9S operating on a service voltage of $E_{phc} = -750$ volts is shown schematically in Fig. 3. In this case, the quantity of incident light flux is obtained by multiplying the area of the aperture of the slit S_3 by the illumination measured with a photoelectric illuminance measuring ap-

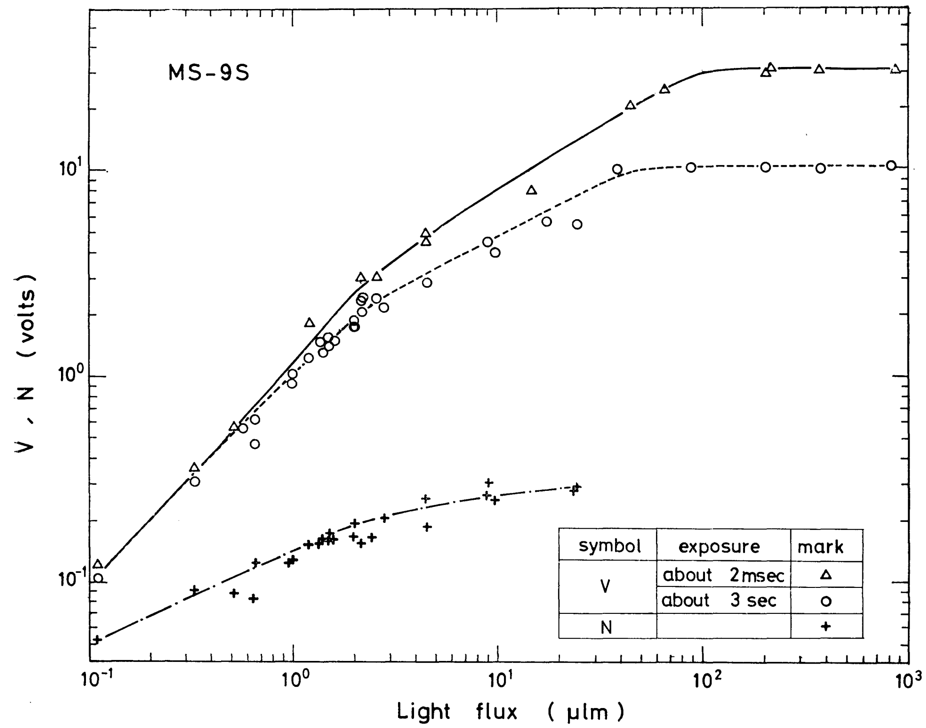


Fig. 3. Relation between the output voltage V and the noise level N of MS-9S and the incident light flux for no disturbances.
Conditions: load resistor=10 KΩ, $E_{phc}=-750$ volts.

paratus: LV-1A of Toshiba Co., Ltd. The dotted line shows the case which light is introduced into the photomultiplier MS-9S continously or about 3 seconds, while the solid line is the case when light is led in it for a short duration of about 2 milliseconds. In the latter, the light regulated with a slit S_h of width 4 mm and height 20 mm which was moved quickly by a hand. A wave from of the output voltage from the MS-9S when much light flux was introduced for about 2 msec by this method is shown in Fig. 4. In this figure, it may be interpreted that the region where the output voltage is low, or the region B corresponds to the period when full light flux enters into the MS-9S through all the aperture of the slit S_h and the region A or C corresponds to just before or after the state. It can be considered that the variation from A to B is due to the saturate and the fatigue of the MS-9S. Therefore, it can not be said exactly that the peak value in the region A is the impulsive output voltage from the MS-9S due to all the incident light flux through out the aperture of the slit S_h. However, we have not found any method to know the exact relation between the incident light flux and the output voltage. Therefore, the authors have assumed the maximum output voltage in the region A or C, mainly the negative higher peak, to be the impulsive

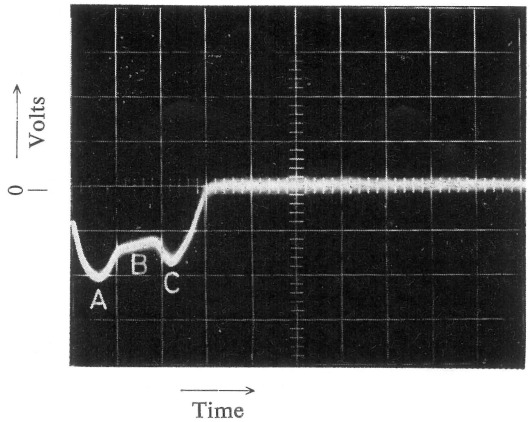


Fig. 4. An output wave form MS-9S by the light through a slit of width 4 mm moved by a hand.
Conditions: load resistor=10 KΩ, E_{phc}=−750 volts.

voltage from the MS-9S for all the light flux though out the aperture of the slit S_h. When the miniature schlieren system was acting with our shock tube, the output voltage, as shown Fig. 11, etc., is higher than the maximum output voltage of the photomultiplier in which case light flux is introduced about 3 seconds (see the dotted line in Fig. 3). This is clearly unreasonable. If the relation between the output voltage and the incident flux shown by the solid line in Fig. 3 is used, the irrationality stated above disappears and the maximum output voltage of the schlieren system under the practical working comdition is always smaller or the same order of magnitude as the maximum output voltage of the static test. Therefore, the assumption of the static performance curve of the output voltage shown by the solid line may be thought to be near to a correct one. All the following experiments correspond to the cases of the very short exposure of the photo-cathode surface. So, these circumstances also indicate reasonability to adopt the static calibration curve of the solid line. Hence, as shown in Fig. 20, the quantities of light flux versus shock Mach numbers is drawn by using the solid line in Fig. 3. Now, some remarks will be added here. The authors' miniature schlieren system and the photomultiplier MS-9S set in the black iron box, $1000\times600\times300$ mm^3 in order to cut off the stray light which may enter into from outside.

2-3. Electric apparatues for experiment

The power supply and the output circuits of the MS-9S are shown in Fig. 5. The potential difference across the load resistor of the MS-9S was led to a wide band amplifier through a cathode follower. The wide band amplifier used in this experiments is a distributed amplifier of Iwasaki Communication Apparatus Co., Ltd. Its frequency response is 0∼30 Mc/s and its gain is 40 db. This amplifier is constructed with the object of supplying an electric field to the deflection plate

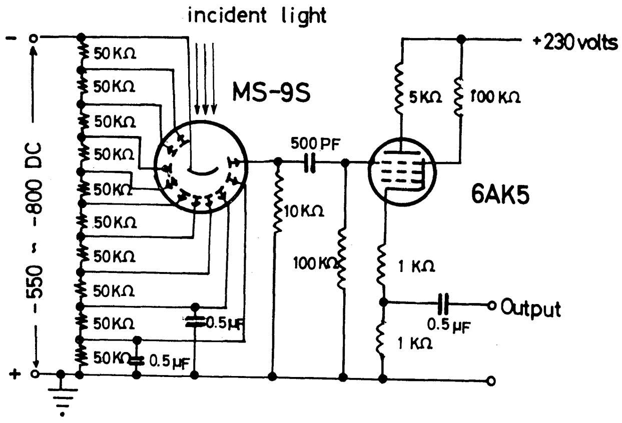


Fig. 5. Circuits of the photomultiplier MS-9S and the cathode follower used.

of a synchroscope, therefore, both of output terminals cannot be earthed. Hence, it cannot be joined to input terminals of a synchroscope and a counter in both of which the negative terminal is always earthed. Therefore, the output signal between one terminal of the wide band amplifier and the ground is transmitted to the counter and the synchroscope. This output voltage was used to trigger the counter and the siynchroscope. Owing to such a use, the combination of the wide band amplifier and the cathode follower shows very poor performance. Its frequency response is about 0~4 Mc/s, over which range its gain changes from 26+3 db at 100 kc/s to 26−3 db at 5 Mc/s. The wide band amplifiers were prepared for the possible low output voltage of the photomultiplier used. But, in the preliminary experiment the authors found that a output voltage of the photomultiplier was considerably higher except the case of a high shock Mach number, so that wide band amplifiers were saturated and the wave forms from them showed the much distortion. Therefore, we used exclusively the electric potential difference across the load resistor of the photomultiplier for the study of characteristics of the miniature schlieren system to obtain the output voltage from the photomultiplier without any effect of the cathode follower and the amplifier. As the authors state above and will be described in later sections, the wide band amplifier is not necessary except the case when the measurement is carried out over a range of a shock Mach number greater than $M_s=2.1$.

The electronic counter is 111D of a vacuum-tube type manufactured in Takeda Riken Co., Ltd. and has resolving power 10 Mc/s. The synchroscope for observing a wave form is SS-5004 of Iwasaki Communication Apparatus Co., Ltd. having the frequency response ranging from D.C. to 15 Mc/s and the rise time of 24×10^{-9} seconds.

2-4. Shock tube

The diagram of the shock tube[6,7] used in this experiments is shown in Fig. 6. The cross section of the tube is $59 \times 150\ mm^2$ area and the pressure of the low pressure chamber can be lowered so far as about 2.5 mm Hg and the high pressure chamber is always maintained at 1 ata.

3. Experiments

3-1. Experimental procedure

In Fig. 6, the high pressure chamber is kept at 1 ata and the pressure of the low pressure chamber is pumped out with a vacuum pump down a desired pressure. After that, if the diaghragm between both chambers is broken with a needle coupled with an electric magnet, a shock wave runs from the left to the right

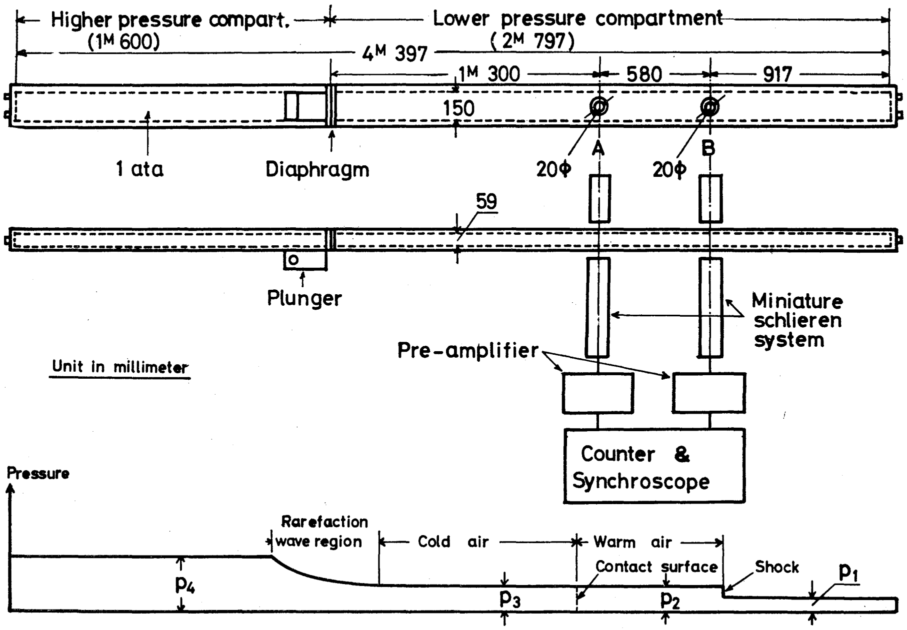
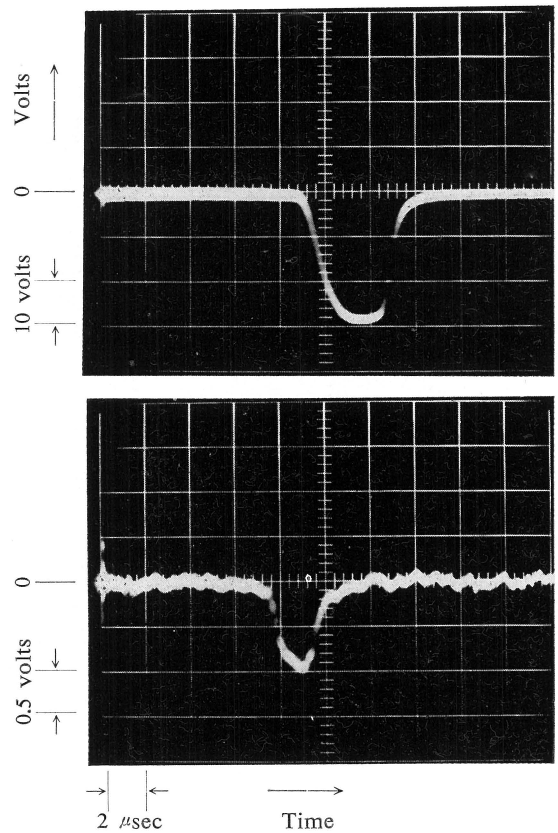


Fig. 6. Schematic diagram of the shock tube and the arrangement of experimental apparatuses.

in the shock tube. The synchroscope and the counter are *started* by the electric pulse from the system *A* and *stopped* by the one of the system *B*. The wave form of the output voltage of the system *B* have used for the study of performance of the miniature schlieren system.

The representative wave form of the output voltage ΔV, produced by the light deflected by a shock wave, across the load resistor of the photomultiplier is shown in Fig. 7.



(*a*) $M_s = 1.309$

(*b*) $M_s = 2.584$

Fig. 7. Wave forms of pulses from the miniature schlieren system.
Conditions: load resistor=10 KΩ, $w_1 = 1.0$ mm, $w_2 = 1.7$ mm, $w_3 = 1.5$ mm, $|h| = 0$ mm, light source =50 watts, $E_{phc} = -750$ volts.

The measurements of the time required for a shock wave to run from A to B was always made simultaneously with the observations of this wave form. The experiments were carried out at pressures in the low pressure chamber of about 200 mm Hg, 120 mm Hg, 80 mm Hg, 50 mm Hg, 17 mm Hg, 8 mm Hg, 6 mm Hg, 4 mm Hg and 2.5 mm Hg, respectively.

The width of the slits were expected to effect upon the working performance of the miniature schlieren system, so that they were selected the following variety of sizes: 1.00* mm in the slit S_1 and 0.5 mm, 1.5 mm and 4.0 mm in the slits S_2 and S_3. Using the system B by various combinations of these values, the authors

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* Liepmann[8] has made the slit S_1 the width of 1.00 mm and Geiger[4] has made it 0.38 mm. For our experiments 1.00 mm has shown the best performance.

were performed experiments.

Now, some considerations on the frequency response of the photomultiplier are given in the following: The authors' experiments were made with an uncompensated load resistor of the photomultiplier, the values of which were ranging from 10 KΩ to 50 KΩ. These values of the resistor are considerably higher as the load resistors of electric apparatuses dealing with the high frequency of the order of several or some ten megacycles. As stated in Section 2–2, the output voltages, produced by the change in incident light by a shock wave, across these resistors will become small and show poor rise characteristics as the width of pulse dealt with in the system gets narrow, because the impednace of resistors decreases due to the stray capacity. In the other word, the frequency response of the photomultiplier with uncompensated resistors cannot be expected to be uniform especially over a range from a wide pulse which corresponds to a low shock Mach number to a narrow pulse which corresponds to a high shock Mach number. However, as seen Table 1, the pulse widths dealt with in the present research is the order of several micro-seconds for a shock Mach number range from 1.3 to 2.6. For example, if the width of $S_3=1.5$ mm, it is from 2 μsec to 3 μsec. This range of pulse width is relatively small. In addition, as seen in Fig. 17, the relative magnitudes of the output voltage ΔV nondimensionalized by the values of the output voltage ΔV at $M_s=1.4$ are 0.56 (at $M_s=2.2$) and 0.23 (at $M_s=2.4$) for a load resistor of 50 KΩ, 0.37 (2.2) and 0.145 (2.4) for 10 KΩ and 0.48 (2.2) and 0.19 (2.4) for 5 KΩ. Accordingly, we cannot find any appreciable effect in the change in these nondimensionalized output voltage for every value of the resistors. This fact also may be interpreted as the stray capacity has little effect on the output from the photomultiplier for a range from $M_s=$ 1.3 to 2.6. So the authors assume that the frequency response of the photomultiplier is uniform within the range of the present experiment. Therefore, the discussion in the following will be made without referring to the frequency response of the photomultiplier.

3–2. Experimental results and discussions

Before describing the experimental results, some qualitative considerations about the sensitivity of the miniature schlieren system will be given here.

In general, when light passes through layers in which the density varies in the x-direction, the sensitivity of an ordinary miniature schlieren system C[8] can be expressed

$$C=\frac{\Delta E}{E}=\frac{\Delta h}{h}=\frac{f_3\cdot L\cdot\beta}{\rho_{st}h}\left(\frac{d\rho}{dx}\right) \qquad \cdots\cdots(1)$$

where

$$\Delta h=f_3\cdot\varepsilon=\frac{f_3\cdot L\cdot\beta}{\rho_{st}}\left(\frac{d\rho}{dx}\right) \qquad \cdots\cdots(2)$$

h = a distance between a knife edge and the edge of the image of the light source shown in Fig. 1 (a).

E = a general illumination on the P-plane which is proportional to h.
Δh = a displacement of the light flux by disturbances.
ΔE = an additional illnmination on the P-plane which is proportional to Δh.
ε = an angular displacement at the lens L_3.
f_3 = the focal length of the lens L_3.
L = the width of layers in which light passes through and the density varies. (in this case, L is the width of the shock tube or 59 mm and is perpendicular to the axis of the shock tube or x-axis).
β = constant in each gas and 0.000292 for air.
ρ_{st} = the density of gas on the standard state.
$\frac{d\rho}{dx}$ = the density gradient in the x-direction.

For an ordinary schlieren system the configuration shown in Fig. 1 (a) is used while in the present miniature schlieren system the light flux is completely cut out by the slit S_2 (Fig. 1 (b)), so that the light reached the slit S_3-plane are only diffracted light. So far as the upper edges of the images do not leave knife edges in both figures of Figs. 1 (a) and 1 (b), and $\Delta h > |h|$ in Fig. 1 (b), the changes in the light on the P-plane in each schlieren system are proportional to Δh and Δh-$|h|$, respectively. On the other hand, in the configulation of the present miniature schlieren system (Fig. 1 (b)), the value corresponding to h in Equation (1) cannot be explicitly defined. Therefore, a function having the dimension of length and the form of $n/n_1 + |h| \equiv f(|h|)$ instead of h have to be used, where n and n_1 are appropriate positive constants and $f(|h|)$ corresponds to the quantity of diffracted light on the P-plane. Thus Equation (1) may be written

$$C = \frac{\Delta E}{E} = \frac{\Delta h - h}{f(|h|)} = \frac{f_3 \cdot L \cdot \beta}{\rho_{st} f(|h|)} \left(\frac{d\rho}{dx}\right) \qquad (1')$$

for the present miniature schlieren system. Inspection of Equation (1′) shows that the additional illumination ΔE is propotional to the density gradient $(d\rho/dx)$, because other factors are constant for the present miniature schlieren system.

Well, let us think about the net additional illumination ΔE_s by a shock wave on the P-plane. The present miniature schlieren system is so arranged that sizes of a shock wave and its image on the slit S_3-plane correspond to 1 : 1. Though the image of a shock wave is very thin, it can be assumed that an additional illumination ΔE on a certain point on the image of the one-dimensional shock layer is approximately proportional to $(d\rho/dx)_s$, viz. the density gradient at a point of the shock wave. Now we shall represent the thickness of the image of a shock wave on the slit S_3-plane by the symbol t_s, and the width of the slit S_3 by the symbol w_3(similarly, the width of the slits S_1 and S_2 are represented by the symbols w_1 and w_2, respectively). As the thickness of a shock wave is considered to be the order of several times of the mean free path of gas molecule, the ratio t_s/w_3 may be very small or about the order of 10^{-3} or 10^{-4}. Hence, it is reasonable that the net additional illumination ΔE_s of the image of the shock wave is equal to the total of the additional illumination at each point in the image. From Equation (1′)

$$\Delta E_s = \int_S \Delta E dx \propto \int_S \left(\frac{d\rho}{dx}\right)_s dx \qquad \cdots\cdots(3)$$

where the integration is made from ahead (symbol *1*) to behind (symbol *2*) of the shock wave. We have

$$\Delta E_s \propto (\rho_2 - \rho_1) \qquad \cdots\cdots(4)$$

Now, we shall discuss the relation between the sensitivity of the present system C_s and the density gradient $(d\rho/dx)_s$ for a shock wave. The nondimensionalzing factors of the each side of Equation (4) are taken a general illumination for no disturbances E_s on the P-plane and the representative density ρ_4 in the low pressure chamber (see Fig. 7). Then, C_s may be considered

$$C_s \propto \frac{\Delta E_s}{E_s} \propto \frac{\rho_2 - \rho_1}{\rho_4} \qquad \cdots\cdots(5)$$

The output voltage of a photomultiplier is a function of incident light flux into its photo-cathode. The quantities discussed above, however, are *illumination* and its changes. But the change in illumination on the slit S_3-plane through which the light enters into the photomultiplier is proportional to the change in the light flux into it. Therefore, the output voltages ΔV by a shock wave and V for no disturbances are proportional to the light fluxes corresponding to ΔE_s and E_s of Equation (5), respectively. Then, Equation (5) is proportional to the ratio $\Delta V/V$ and may be written

$$C_s \propto \frac{\Delta E_s}{E_s} \propto \frac{\rho_2 - \rho_1}{\rho_4} \propto \frac{\Delta V}{V} \qquad \cdots\cdots(6)$$

In our experiments, ΔV is measured after V is adjusted to the zero line of the synchroscope, while the measurements of noise level N from the photomultiplier is made for each experiment at the beginning and end of the experiments. Here, by the noise level we mean kinds of dark current of very high frequencies. This high frequencies noise cannot be exactly measured, because the frequency response of our electric apparatuses is flat up to 4 Mc/s at most. Therefore, the value of the noise level within the present experiment is the apparent value read from the height of the figure of the noise on Braun tube. The true voltage of the noise must be higher than this value. As stated above, V and N are the values for no disturbances and are constant during the measurement of shock velocity. N increases with the rise of V (compare V with N in Fig. 3). So long as the output voltage ΔV is proportional to the incident light flux, the increase in V due to a general light flux, which is one of back ground has little effect on ΔV from the photomultiplier (see V and ΔV curves in Fig. 11). As V and N are constant during the measurements, both can be used as a nondimensionalizing factor. However, if ΔV is less than or comparable to N, ΔV cannot trigger the electric experimental apparatuses or a synchroscope and a counter.

Accordingly, N is more suitable than V as a nondimensionalizing factor of ΔV for the present research. Therefore, we put

$$C_s \propto \frac{\Delta E_s}{E_s} \propto \frac{\Delta V}{V} \propto \frac{\Delta V}{N} \qquad \cdots\cdots(7)$$

On the other hand, from the shock-tube theory for air, the relation between the shock Mach number M_s and $(\rho_2-\rho_1)$ is

$$\frac{\rho_2-\rho_1}{\rho_4} = \frac{\rho_1}{\rho_4} \cdot \frac{\frac{2}{\gamma-1}(M_s^2-1)}{M_s^2+\frac{2}{\gamma-1}} \qquad \cdots\cdots(8)$$

where γ is the ratio of specific heats and 1.4 for air. Then, from Equations (6), (7) and (8), $\Delta V/N$ can be expressed as a function of M_s.

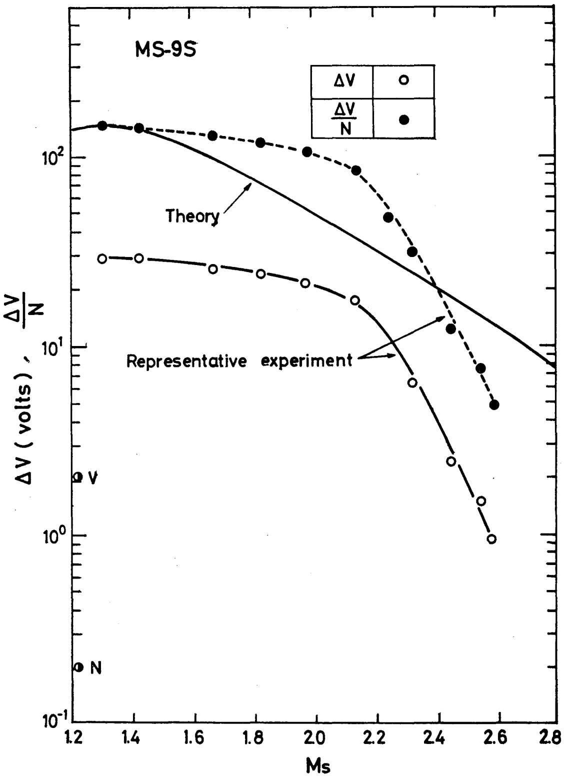


Fig. 8.* Comparision of theory with experiment. Conditions : load resistor = 10 KΩ, $w_1 = 1.0$ mm, $w_2 = 1.7$ mm, $w_3 = 1.5$ mm, $|h| = 0$ mm, light source=50 watts, $E_{phc}=$ -750 volts.

* The theoretical curve shows the values of $\frac{\rho_2-\rho_1}{\rho_4}\times 10$ versus M_s under the conditions of $P_4 = 760$ mm Hg and $T_1=T_4=290$°K.

In Fig. 8, the theoretical curve is calculated from Equations (6), (7) and (8), and multiplied by a factor of 10^3. This calculated curve qualitatively agrees with one of the experimental curves. A fractor of 10^3 is used for the purpose of rendering the absolute value caluculated and the experimental value to the same order of magnitude. As stated before, the authors' experiments were carried out by pumping out the low pressure chamber with a vacuum pump and maintaining the high pressure chamber at 1 ata. Therefore, as M_s increase, both ρ_2 and ρ_1 decrease and its defference $(\rho_2-\rho_1)$ also decreases.

On the inspection of Equations (6), (7) and (8), it can be interpreted that ΔV and $\Delta V/N$ decrease as the decrease in the light flux deflected through a shock layer. This theoretical and experimental curves subtantiate well the tendency stated just above. Moreover, the experimental curve of Fig. 8 shows the abrupt decrease in slopes at a shock Mach number of 2.2. But this tendency could not be explained by the theoretical consideration.

In the experimental curve of Fig. 8, $\Delta V/N=4$ and $\Delta V=0.9$ volts at $M_s \doteqdot 2.6$. As this, when ΔV and $\Delta V/N$ became small, the reliability upon the trigger function of all the system for measurements of shock velocity became low. The low pressure chamber of our shock tube was unable to pumped out up to 2.5 mm Hg, so that the maximum M_s which was able to be measured in the present miniature schlieren system could not be exactly determined. But the system certainly worked up to about $M_s \doteqdot 2.5$, while, for $2.5<M_s<2.6$, the error in triggering the system was not a few. Even if $M_s \doteqdot 2.6$, which corresponds to 2.5 mm Hg, measurements of shock velocity could be carried out, but it was necessary that the system was to be carefully adjusted.

Being the curve in Fig. 8 extroplated, $\Delta V/N$ approaches to a unity for $M_s>2.6$, therefore $M_s=2.6\sim2.7$ may be thought to be the working limit of our miniature schlieren system. As above-mentioned, near this critical shock Mach numbers the performance of the presemt system must be discussed by not only ΔV but also $\Delta V/N$, so that in the sections of *experimental results and discussions* both of ΔV and $\Delta V/N$ are shown. ΔV will serve to select these kinds of counters and pre-amplifiers, and $\Delta V/N$ with ΔV will used to determine the maximum shock Mach number which these apparatuses are able to measure. Therefore, in the following discussions, not only ΔV but also $\Delta V/N$ are shown with the abcissa of M_s.

Now, the relations of ΔV and $\Delta V/N$ to the width of the slit S_3, the value of $|h|$ on the slit S_2-plane, the brightness of the light source and other elements will be shown and discussed in the following.

3–2–1) *Relation of the service voltage of the photomultiplier to ΔV and $\Delta V/N$*

Fig. 2 (b) shows that the multiplication of a photomultiplier is determined by a service voltage, more precisely speaking, a photo-cathode voltage E_{phc} (negative volts). At first, by maintaining the condition of the miniature schlieren system at the state before the arrival of a shock wave at the test-section, V

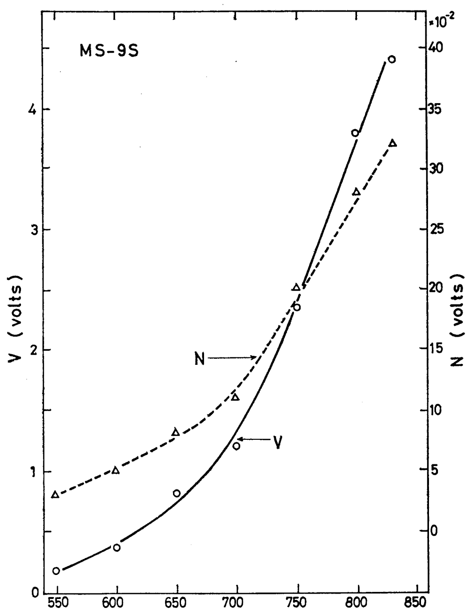


Fig. 9. Relation between the output voltage for no disturbances and the noise level and the service voltage.
Conditions: load resistor $=10$ KΩ, $w_1=1.0$ mm, $w_2=1.5$ mm, $w_3=1.5$ mm, light source$=50$ watts, $|h|=0$ mm, light flux for no disturbances F_{nd} on the P-plane$=2.17$ μlm.

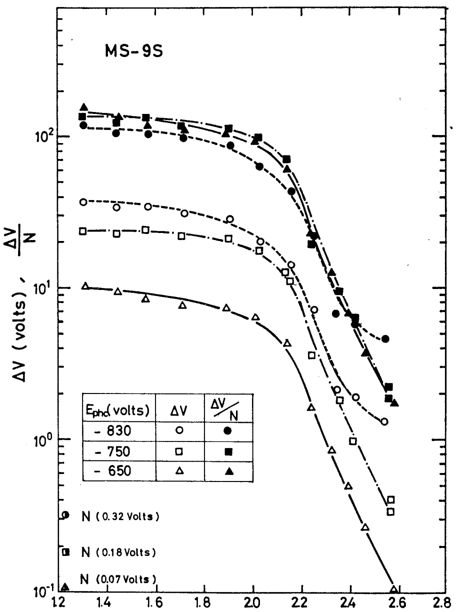


Fig. 10. Variation of the output voltage ΔV and the output-to-noise ratio $\Delta V/N$ due to the service voltage.
Conditions: load resistor $=10$ KΩ, $w_1=1.0$ mm, $w_2=1.5$ mm, $w_3=1.5$ mm, $|h|=0$ mm, $F_{nd}=2.26$ μlm, light source$=50$ watts.

and N of the photomultiplier MS-9S for a light flux of 2.17 μlm were measured by changing E_{phc}. Fig. 9 shows this results and the experimental conditions are shown at the bottom. In this figure, V and N increase with the absolute value of a service voltage. Therefore, though ΔV will increase with E_{phc} under the practical working condition, $\Delta V/N$ will not become so large.

Now, the change in the performance of the miniature schlieren system by E_{phc} is shown in Fig. 10. This is the experimental result obtained by running the shock tube. The values of E_{phc} were -650 volts, -750 volts and -830 volts. The group of curves of signs painted out is $\Delta V/N$ and the group of hollow signs is ΔV. The noise level N for no disturbances are shown by the half-painted signs,(similarly, the output voltage V for no disturbances are shown by the half-painted signs in Figs. 11 to 19). The experimental conditions are written at the bottom. In the case of $E_{phc}=-830$ volts, though the output voltage is high, the noise level also is high, so that $\Delta V/N$ is bad. Moreover, the working of the system was unstable. In both cases of $E_{phc}=-650$ volts and -750 volts, the working of the system was stable, but the out put voltage is low in the case of $E_{phc}=-650$ volts. Consequently, we find that $E_{phc}=-700\sim750$ volts is suitable for our experiment.

As far as the special notice is not given in the following, the photomultiplier used is MS-9S and $E_{phc}=-750$ volts.

3-2-2) *On the slit* S_3

The symbol F_{nd} means the light flux which is introduced into the photocathode surface of MS-9S through the aperture of the slit S_3 before or after the arrival of a shock wave. It is proportional to the width of the slit S_3 or w_3, since the height of this slit is constant or 11 mm. As stated before, it is the main function of the slit S_3 to restrict the incident light flux beyond necessity

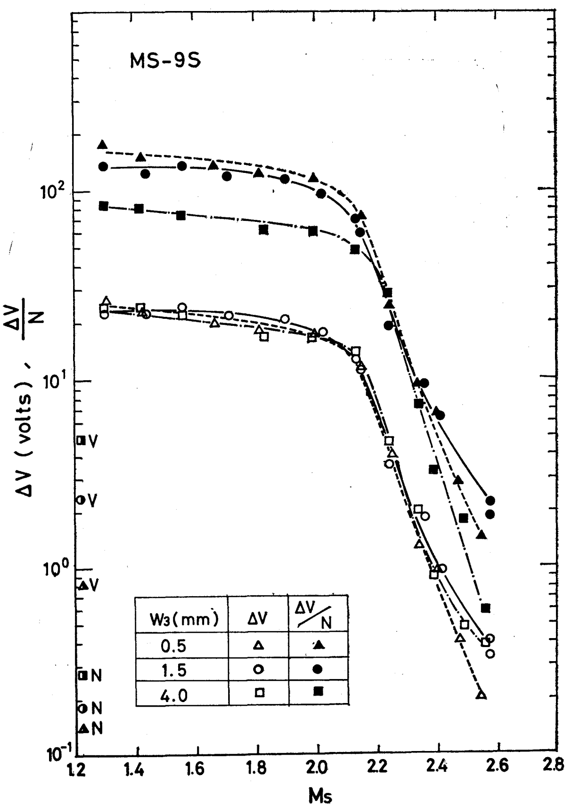


Fig. 11. Variation of ΔV and $\Delta V/N$ due to the width of slit S_3.
Conditions: load resistor $=10\,K\Omega$, $w_1=1.0$ mm, $w_2=1.5$ mm, $w_3=$variable, $|h|=0$ mm, $E_{phc}=-750$ volts, light source $=50$ watts, $F_{nd}=0.22$ μlm for $w_3=0.5$ mm, 2.17 μlm for $w_3=1.5$ mm, 23.46 μlm for $w_3=4.0$ mm.

into the MS-9S, while it serve to reduce the noise level due to diffracted light.

The relation between w_3 and ΔV and $\Delta V/N$ is shown in Fig. 11. The case of $w_3=4$ mm shows inferiority in $\Delta V/N$ to the other cases. The probability of success in triggering the time counting system was also smaller. This seems to be due to its high noise level, because F_{nd} is about 22.2 μlm~24.7 μlm, so that the working state of the MS-9S is near its saturation condition (see Fig. 3). Hence, as seen in Fig. 11, $w_3=0.5$ mm~1.5 mm will be suitable for our apparatuses, then F_{nd} is about 0.246 μlm~2.46 μlm, where these values of F_{nd} are obtained by reading Fig. 3 from V of Fig. 11.

Moreover, it was found that the pulse width of output wave form was approximately calculated from w_3 and shock velocity. About this result a precise discussion will be given in Section 3-2-10.

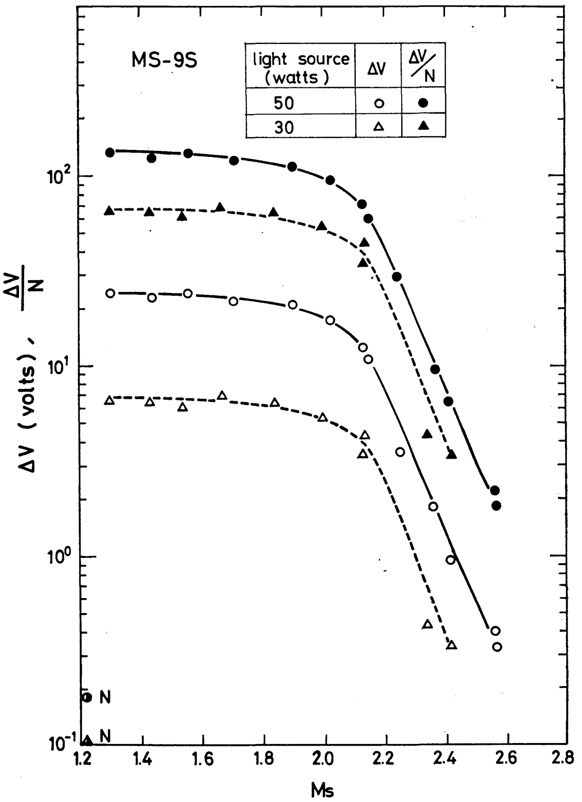


Fig. 12. Variation of ΔV and $\Delta V/N$ due to brightness of the light source.

Conditions: load resistor=10 KΩ, $w_1=1.0$ mm, $w_2=1.5$ mm, $w_3=1.5$ mm, $|h|=0$ mm, $E_{phc}=-750$ volts, $F_{nd}=2.26$ μlm for a light source of 50 watts, $F_{nd}=0.62$ μlm for a light source of 30 watts.

3-2-3) *Relation between the brightness of the light source and* ΔV and $\Delta V/N$

The illumination of a schlieren image is proportional to the brightness of a light source[9].

How does the brightness of the light source effect on the performance of the miniature schlieren system? In order to obtain some informations about this quation, the experiments with two kinds of watts of 30 watts and 50 watts supplied the bulb were made. The experimental results are shown in Fig. 12. In the case of 30 watts, the output voltage ΔV becomes about 1 volt and $\Delta V/N$ becomes 10 at $M_s=2.3$. By this low output voltage of 1 volt the counter (whose lower limit of trigger level is ± 2 volts) used in the present experiment cannot be *started* and *stopped* and the synchroscope SS-5004 also cannot be *triggered*. So the wide band amplifiers with the cathode follower for impedance matching (see Section 2-3) were used to amplify the output voltage up to the suitable trigger voltage. In this case, even if the output voltage was amplified, the reliable working of the system could be expected up to a shock Mach number of 2.43 at the most, because $\Delta V/N$ approcahed to a unity. In the case of 50 watts, measurements of shock velocity were possible up to $M_s \doteqdot 2.6$, which corresponds to the minimum pressure of 2.5 mm Hg in our low pressure chamber. Though the present experiments are carried out only for these two cases, we may say that 50 watts or the rating of the bulb are good as a watt-age for the light source of our apparatuses.

3-2-4) *On the width of the slit* S_2 *with a knife edge*

In Fig. 1 (b), the configulation of the slit S_2 used in our experiments is illustrated. This slit S_2 is the rectangular aperture with height 11 mm, whose width can be varied over a range from 0 mm to 5 mm. The one edge by which the image of the light source is shielded is a schlieren knife edge, the other on the opposite side is attached to restrict the incident light flux into the photomultiplier. In the present experiments, the values of w_2 are 0.5 mm, 1.5 mm and 4.0 mm and the image of the light source on the slit S_2-plane is width 1.5 mm and height 11 mm.

Fig. 13 shows the experimental results. In the case of $w_2=0.5$ mm, $\Delta V/N$ is larger or smaller than the other cases, according as $M_s>2.15$ or $M_s<2.15$. The low noise level in the case of $w_2=0.5$ mm may be one of the causes of superior performance of $\Delta V/N$ for $M_s>2.15$. The small $\Delta V/N$ for $M_s<2.15$ may be interpreted as the followings: $w_2=0.5$ mm is probably smaller than the displacement of light flux, viz. Δh on the slit S_2-plane due to a shock wave. Then, the deflected light is cut off again by the opposite edge of the slit S_2, so that ΔE_s or ΔV become smaller than the other cases. When $w_2=4.0$ mm, $V=4$ volts for no disturbances and $N=0.25$ volts in Fig. 13. Seeing the light flux corresponding to these V and N in Fig. 3, we find that the photomultiplier MS-9S is just before its saturation. Therefore, the case of $w_2=4.0$ mm should be kept out. On the basis of these experimental facts, it is concluded that the suitable value of w_2 is 0.5 mm$\sim$1.5 mm. If any notice is not given, w_2 is 1.5 mm in the other sections of

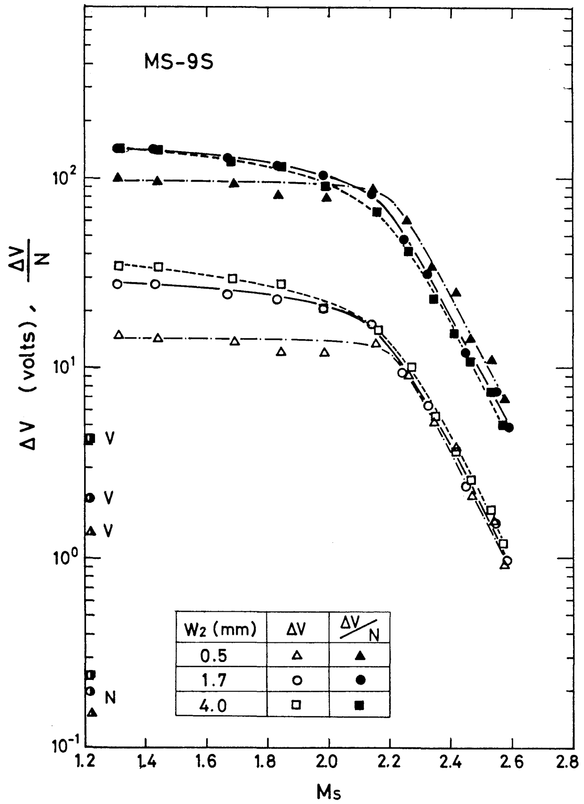
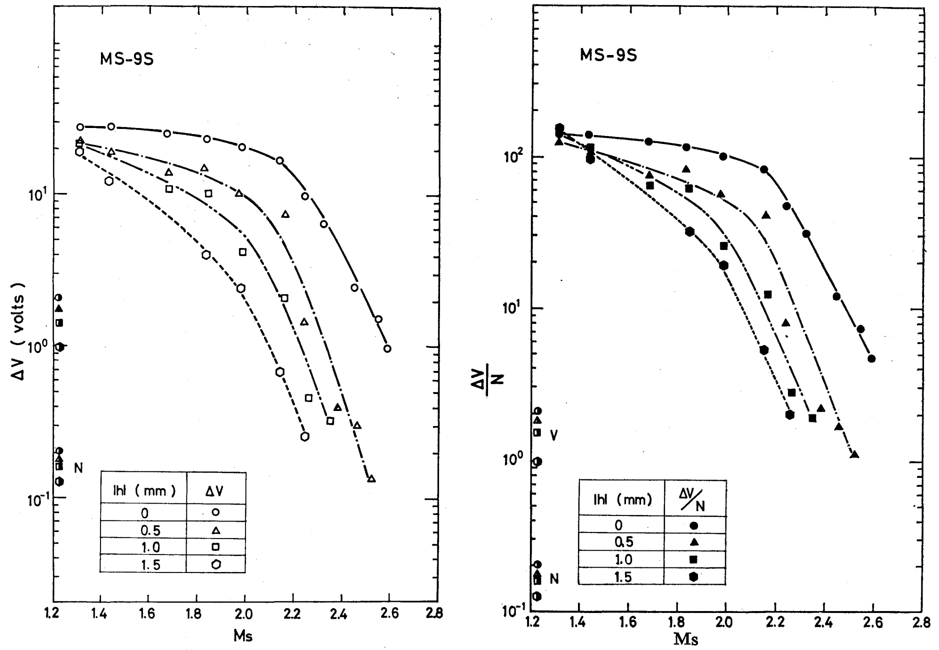


Fig. 13. Variation of ΔV and $\Delta V/N$ due to the width of slit S_2.
Conditions: load resistor=10 KΩ, w_1=1.0 mm, w_2=variable, w_3=1.5 mm, $|h|$ = 0 mm, E_{phc} = −750 volts, F_{nd}=1.35 μlm for w_2=0.5 mm, F_{nd} =2.83 μlm for w_2=1.7 mm, F_{nd}=19.75 μlm for w_2 =4.0 mm, light source=50 watts.

this paper.

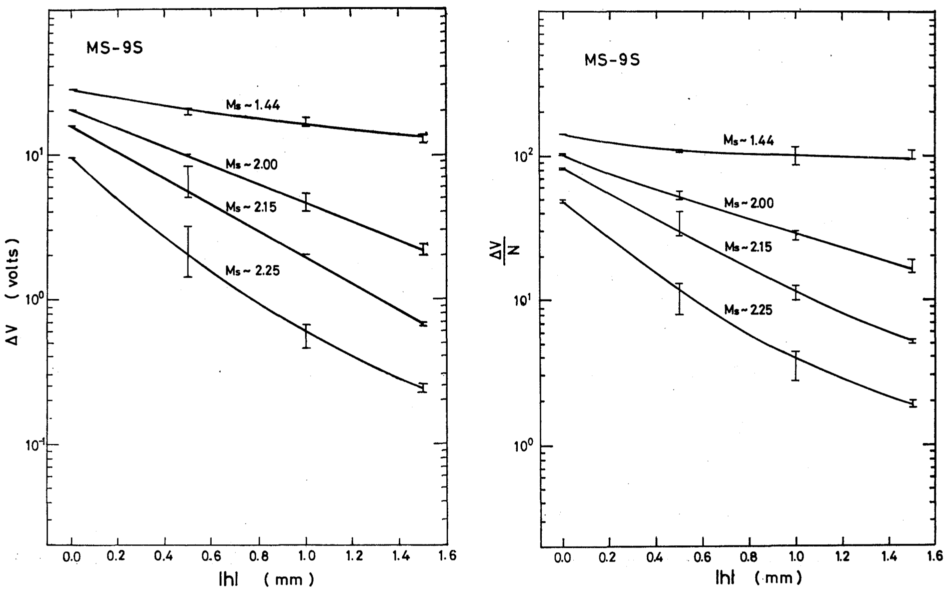
3-2-5) *Effect of* $|h|$ *upon* ΔV *and* $\Delta V/N$

Explanation of $|h|$ is given in Fig. 1 (b). As Equation (1′) shows, the longer the focal length f_3 of the lens L_3 and the shorter the distance $|h|$ of the knife edge from the edge of the light source which determines a general illumination E_s by diffracted light, the sensitivity of the miniature schlieren system will become the better. The experiments for the effect of this $|h|$ on the performance of the system were made for the four cases of $|h|$ = 0 mm, 0.5 mm, 1.0 mm and 1.5 mm with the lens of f_3=240 mm, but the experiments for various values of f_3 were not performed. The results obtained are shown in Figs. 14 (a) and 14 (b). In



(*a*) (*b*)

Fig. 14. Effect of the distance of the knife edge from the image of light source upon ΔV and $\Delta V/N$. (*a*) ΔV. (*b*) $\Delta V/N$.
Conditions: load resistor=10 KΩ, w_1=1.0 mm, w_2=1.7 mm, w_3=1.5 mm, light source=50 watts, F_{nd}=2.83 μlm for $|h|$=0 mm, F_{nd}=2.02 μlm for $|h|$=0.5 mm, F_{nd}=1.52 μlm for $|h|$=1.0 mm, F_{nd}=0.98 μlm for $|h|$=1.5 mm.



(*a*) (*b*)

Fig. 15. Relation between ΔV and $\Delta V/N$ and $|h|$. (from Figs. 14 (*a*) and (*b*)). (*a*) ΔV. (*b*) $\Delta V/N$.

the case of $|h| = 0$ mm, ΔV and $\Delta V/N$ are obviously larger than the other cases, and in this arrangement measurements of shock velocity were able to be as far as the minimum pressure of 2.5 mm Hg (corresponding to $M_s \fallingdotseq 2.6$) of our shock tube with much reliability. Figs. 14 (a) and 14 (b) are rewritten with M_s as a parameter and these are shown in Figs. 15 (a) and 15 (b) by taking $|h|$ as the abscissa. From these results, it may be said that, for the superior performance of the system, the knife edge must be coincident with the edge of the image of the light source and just blocks out the image of the light source, that is, $|h| = 0$ mm. In this case, the color of the image of the test-section on the slit S_3-plane was just like dark purple. The experimental data without any remark about $|h|$ described in this report is the one obtained when $|h| = 0$ mm.

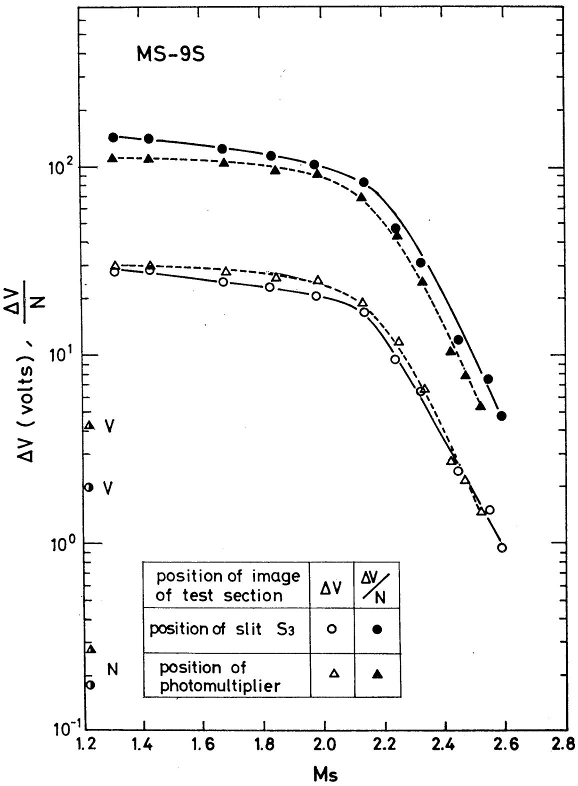


Fig. 16. Effect of the position of the image of test-section upon ΔV and $\Delta V/N$.

Conditions: load resistor = 10 KΩ, $w_1 = 1.0$ mm, $w_2 = 1.7$ mm, $w_3 = 1.5$ mm, $|h| = 0$ mm, light source = 50 watts, $E_{phc} = -750$ volts, $F_{nd} = 2.83$ μlm when the slit S_3 is located at the position of the image of test-section, $F_{nd} = 9.43$ μlm when the photo-cathode surface of the photomultiplier is placed in the position of the image of test-section.

As the displacement of light flux is proportional to the focal length of the schlieren lens L_3 or f_3, the above results may be changed in various senses if a lens of a different focal length from the present case is used.

3-2-6) *On the position of the image of the test-section*

The experiments were made with two arrangements in which there was the slit S_3 at the position of the image of the test-section and the photo-cathode surface at it, respectively. As seen in Fig. 16, there was no significant difference in the curves of ΔV versus M_s between the two arrangements. On the other hand, V and N are slightly lower and $\Delta V/N$ is greater in the former. Therefore, the case that the slit S_3 is set at the position of the image of the test-section is suitable for our apparatuses.

3-2-7) *Relation between the load resistor of the photomultiplier MS-9S and ΔV and $\Delta V/N$*

As the experimental results shown in Fig. 17, ΔV and $\Delta V/N$ become large

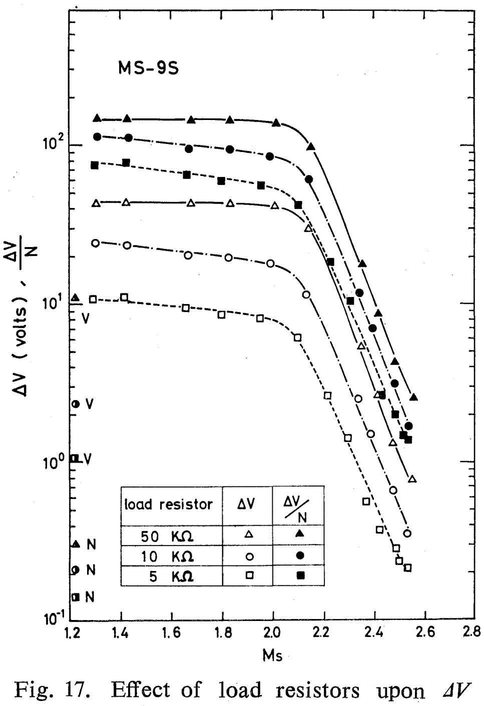


Fig. 17. Effect of load resistors upon ΔV and $\Delta V/N$.
Conditions: $w_1=1.0$ mm, $w_2=1.7$ mm, $w_3=1.5$ mm, $|h|=0$ mm, $E_{phc}=-750$ volts, light source=50 watts, $F_{nd}=2.46$ μlm.

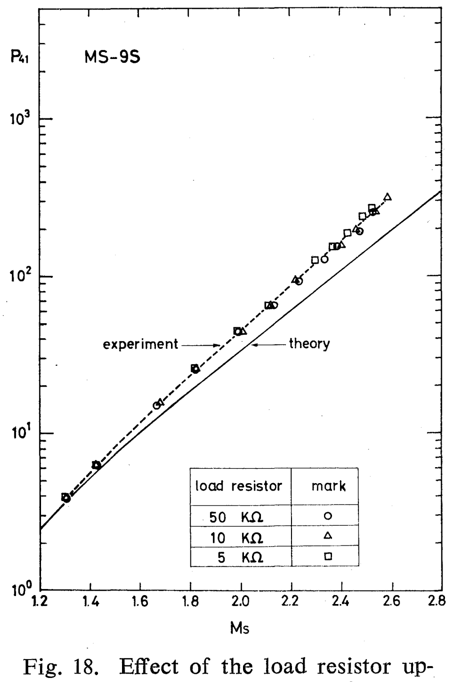


Fig. 18. Effect of the load resistor upon measurements of shock Mach number.
Conditions: $w_1=1.0$ mm, $w_2=1.7$ mm, $w_3=1.5$ mm, $|h|=0$ mm, light source $=50$ watts, $E_{phc}=-750$ volts, $F_{nd}=2.46$ μlm.
Remark: $p_{41}=p_4/p_1$ (see Fig. 6).

with an increase in the load resistor. The measurements of shock velocity were possible up to about a shock Mach number of M_s=2.6 in each case of 5 KΩ, 10 KΩ and 50 KΩ. In Fig. 18, three kinds of marks show the shock Mach numbers, for initial pressure ratios of p_4/p_1, measured by each resistor, while the solid line shows the shock Mach numbers calculated from shock-tube theory. The experimental values for each load resistor are found on a nearly common line. The difference between theoretical and experimental curves is due to the effect of viscosity. It was expected that a time response or a rise time became worse as the value of the load resistor became large, because the effect of stray capacity of resistor appeared to be predominant. However, the maximum values of the rise time was 0.5～1.5 μsec in each resistor. These values are considerably larger compared with the pulse width of the output voltage (see Table 1), but have little contribution to the duration of the order 600 μsec which takes for a shock wave to travel from A to B (see Fig. 6). Therefore, this order of rise time had no effect on our measurements of shock velocity. On the basis of these experimental facts, it is concluded that the load resistor for the photomultiplier used to the present purpose is selected over a reange of 5 KΩ ～50 KΩ. The load resistor of 10 KΩ is used mainly in this experiments, because this value is the rating for MS-9S.

3-2-8) *Comparision of MS-9S with 7696*

The photomultiplier MS-9S has nine dynodes, while the 7696 has ten dynodes. The multiplication μ of the MS-9S is larger than one of the 7696 for the same service voltage (see Fig. 2 (b)). The present experimental conditions of the MS-9S are $E_{phc}=-750$ volts and $\mu=2\times10^5$, and one of the 7696 are $E_{phc}=-850$ volts and $\mu=2\times10^4$.

Fig. 19 shows the comparision of the MS-9S with the 7696 in regard to ΔV and $\Delta V/N$. The multiplication of 7696 is one-tenth of that of MS-9S, but the maximum output voltage is about 8 volts against about 30 volts of the MS-9S in the present arrangement. On the other hand, $\Delta V/N$ of the 7696 is inferior or superior to one of the MS-9S, according as $M_s<2.1$ or $M_s>2.1$. This may be due to the very low noise level of the 7696. Under this experimental conditions, the 7696 showed more stable working behavior of the system than one of the MS-9S in the region of a high shock Mach number where the very critical adjustment was required.

As the authors stated in Section 3-2-1, if the absolute value of E_{phc} was made small (that is, μ was small) in the MS-9S, the working behavior was stable, because the noise level became low. The 7696, however, seems to have the very extraordinary low noise level as its specific quality. The low output voltage of the 7696 can be covered by using a counter with a low trigger level. In our experiments, the electronic counter with a trigger level of ±2 volts was used, so that the 7696 with a low output voltage could not be used without the very good wide band pre-amplifier. However, if a transistor-type counter with a low trigger level is used, the 7696 may be used in a miniature schlieren system and may show superior performance. In the present stage of our study, therefore

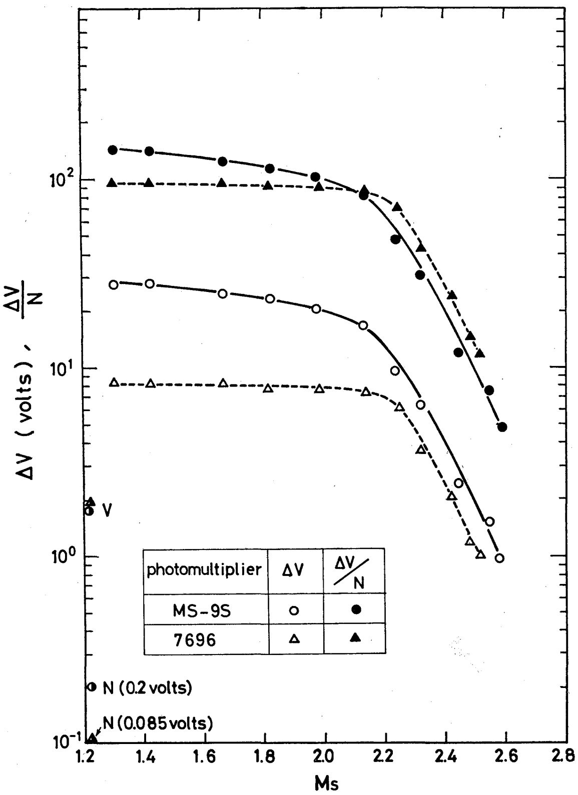


Fig. 19. ΔV and $\Delta V/N$ of photomultipliers MS-9S and 7696.

Conditions: load resistor=10 KΩ, w_1=1.0 mm, w_2=1.7 mm, w_3=1.5 mm, light source=50 watts, F_{nd}=2.83 μlm, service voltage of MS-9S=−750 volts, service voltage of 7696= −850 volts, $|h|$= 0 mm.

it may be said that either of MS-9S and 7696 can be used for the miniature schlieren system according to the kinds of counters used.

3-2-9) *The incident light flux calculated from the output voltage by a shock wave*

In the present experiments, as the order of time irradiated by incident light on the photo-cathode surface of the photomultiplier, which is calculated from the pulse width of an output signal, is below 10 μsec, it will be reasonable that the characteristic curve of the solid line in Fig. 3 is used to calculate the incident light flux from the value of $\Delta V+V$.

Fig. 20 drawn by the above method is an example of the relations between M_s and the total incident light flux for $\Delta V+V$ into the photo-cathode by a shock wave. It may be found that the incident light flux which is so much as to

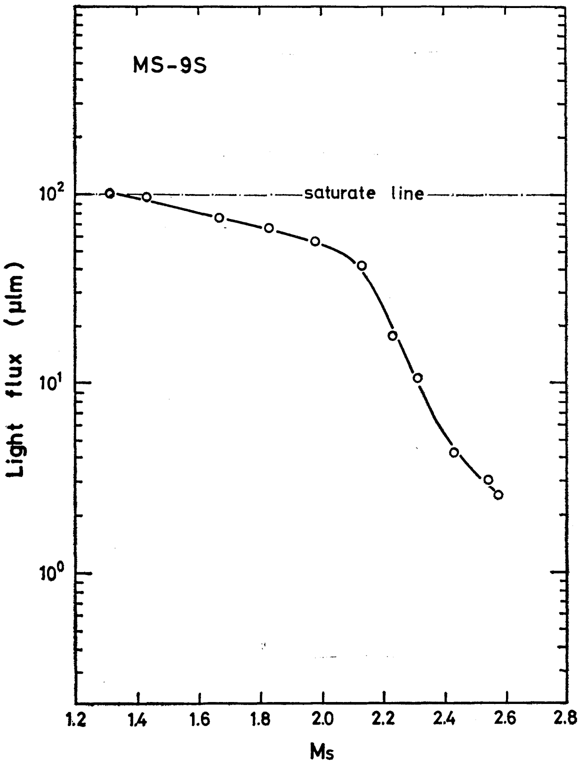


Fig. 20. Relation between the intensity of deflected light and shock Mach number.
Conditions: load resistor=10 KΩ, w_1=1.0 mm, w_2=1.7 mm, w_3=1.5 mm, $|h|$=0 mm, light source =50 watts, E_{phc}=−750 volts.

saturate the MS-9S is introduced into it by the shock wave up to about $M_s=1.4$. As M_s increases, the incident light flux decreases and is 55 μlm at $M_s \doteqdot 1.98$ and 2.5 μlm at $M_s \doteqdot 2.58$, which is the highest shock Mach number in the present experiments.

3-2-10) *A band width required to electric circuits of the system*

If a nominal signal duration used in telecommunication engineering is described by the symbol $2t_n$, a nominal cut-off frequency f_n[10] of an electric system is expressed as follows:

$$f_n = \frac{1}{4t_n}$$

The nominal cut-off frequency means the maximum frequency up to which the spectrum of frequency is constant.

According to electronic theory, in order to reproduce or amplify the pulse exactly whose cut-off frequency is f_n, the electric apparatuses having cut-off frequency of $10f_n$ are necessary. Therefore, in present case, the cut-off frequency of the wide band amplifier with cathode follower connected to the photomultiplier must be tenth as large as a nominal cut-off frequency of an input pulse. In the following, we shall examine whether our apparatuses satisfy this condition or not.

The experimental nominal cut-off frequency was calculated from the pulse width of the output signal in the present experiments, while the calculated nominal cut-off frequency was obtained from w_3 and the shock velocity. The results are shown in Table 1. In the column of *experimental values*, the nominal

TABLE 1. Nominal cat-off frequency

Shock wave		Width of slit S_3	Experimental values			Calculated values (rectangular pulse)		
M_s	Shock velocity (mm/μsec)	w_3 (mm)	Pulse width(μsec) Half-value width	Pulse width(μsec) $2t_n$	f_n (Mc)	$2t_n$ or Half-value width (μsec)	f_n (Mc)	$10f_n$ (Mc)
1.304	0.445	4.0	8.0	7.70	0.065	8.99	0.056	0.56
1.309	0.444	1.5	3.2	3.25	0.154	3.38	0.148	1.48
1.301	0.445	0.5	1.3	1.40	0.357	1.12	0.446	4.46
2.392	0.816	4.0	4.4	4.53	0.110	4.89	0.103	1.03
2.446	0.831	1.5	2.0	2.05	0.244	1.81	0.277	2.77
2.392	0.817	0.5	0.8	1.00	0.500	0.62	0.817	8.17
2.584	0.878	1.5	1.8	2.00	0.250	1.71	0.293	2.93

signal duration $2t_n$ means the width of the rectangular pulse whose wave height and area are equal to one of the output pulse obtained in the present experiments, and the half-value width is the pulse width where the wave height becomes one half its maximum. In the column of *calculated values*, the nominal signal duration $2t_n$ and the half-value width are the time for the image of a shock wave to pass through the width w_3 of the slit S_3. These are calculated from dividing w_3 by the shock velocity U, because, as the authors stated in the previous section, dimensions of an obstacle in the test-section and its image on the slit S_3-plane correspond to each other 1 : 1.

We find the followings from Table 1: for values of M_s given in the first column, the experimental nominal cut-off frequencies in the sixth column which are calculated by using the output pulses obtained are nearly equal to the calculated nominal cut-off frequencies in the eighth column. In addition, in both *experimented values* and *calculated values*, the nominal cut-off frequency are in inverse proportion to w_3, while the nominal signal duration and the pulse width are proportional to w_3. The last results are shown in Fig. 21 with w_3 in the

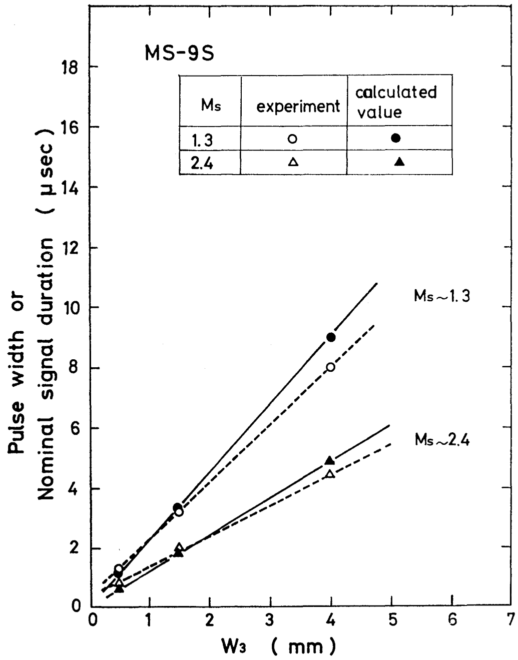


Fig. 21. Relation between the width of slit S_3 and the pulse width or the nominal signal duration. Conditions: load resistor=10 KΩ, w_1=1.0 mm, w_2=1.5 mm, $|h|$=0 mm, E_{phc}=−750 volts, light source=50 watts.

abscissa and $2t_n$ in the ordinate. The experimental values and the calculated values agree to each other within the error of ten per cent. Therefore, if w_3 and the order of a shock velocity to be measured are given, the order of a nominal cut-off frequency of the pulse which will be produced by the miniature schlieren system can be calculated. By using this value, the upper limit of the frequency response required to electric circuits of the system can be determined. For example, for M_s=2.392 in the sixth row, the nominal cut-off frequency is f_n=0.5 Mc/s in the experimental value and is f_n=0.817 Mc/s in the calculated value. Therefore, as above-mentioned, the frequency response of electric circuits of the system is desirable to be sure up to 8 Mc/s which corresponds to $10f_n$.

Since the frequency response of the synchroscope SS-5004 and the electronic counter 111D used are 0~15 Mc/s and 0~10 Mc/s, respectively, these satisfy the above conditions. As the upper limit of the frequency response of the wide band amplifier including the cathode follower used is 4 Mc/s (see Section 2-3), this instrument has poor performance for our system.

If we desire to make the upper limit of the frequency band of electric circuits small, it is sufficient only to make w_3 large. This case corresponds to the case of w_3=4 mm in our experiments. On the occasion, the photo-cathode of MS-9S was exposed to much quantity of light before the shock arrival and too much light flux at the moment of the shock arrival during relatively long time (see Section 3-2-2). Therefore, this configulation is not favorable to performance and life of the photomultiplier. On the other hand, if w_3=0.5 mm, the upper limit of the frequency response of electric apparatuses has to be beyond 8 Mc/s. In the latter case, though the range of the frequency required is wide, fatigiue of the MS-9S is little and the sensitivity of the miniature schlieren system is good. Hence, we consider that, for the suitable value of w_3 between 0.5 mm and 1.5 mm (see Section 3-2-2), the upper limit of the frequency response required is between about 3 Mc/s and 8 Mc/s. This may be the reasonable value for this kind of apparatus in the points of production and economy and so on.

Furthermore, we find in Table 1 and Fig. 21 that the pulse width (half-value width and $2t_n$) of the output signal is approximately equal to the calculated pulse width, therefore a shock velocity U may be estimated from the formula of $U=w_3/2t_n$ to a considerable accuracy. In the present stage, the calculated values of shock veolcity agree with experimental values to an accuracy of about 10% (see Fig. 21). The error may be mainly due to the poor performance of the present experimental apparatuses. If performance of the optical system and frequency characteristic of the electric apparatuses are improved, this error will become smaller. Nevertheless, it may be suggested that measurements of shock velocity may be made to a considerable accuracy only a position of a range of several millimeters. Then, measurements of decay of shock velocity, observations of development of an unsteady shock wave, etc. will be easily performed to the higher accuracy than the two points method which has been used.

3-2-11) *Combination of the miniature schlieren system with the wide band amplifier*

For measurements of a high shock Mach number, a small output voltage from the miniature schlieren system below the trigger voltage of the synchroscope and the time counter has to be amplified. For this amplification, a cathode follower for impedance matching and a wide band amplifier for amplification are provided between the synchroscope and the counter and the miniature schlieren system. In the present experiments, the cathode follower circuit in Fig. 5 and the wide band amplifier of Iwasaki Communication Apparatus Co., Ltd. manufacture are used. The gain of the combined circuits is 26+3 db at 100 Kc/s and 26−3 db at 5 Mc/s (see Section 2-3).

The representaitve wave form of the output voltage are shown in Fig. 22 and the representative curve of the change in the output votage is shown in Fig. 23. Though the wave form of the input signal, which is the potential difference across the load resistor of the MS-9S, into the wide band amplifier is the pulsive form as shown in Fig. 7, the wave form of the output signal from it shows the overshot as shown in Fig. 22.

The maximum shock Mach number up to which the wave showed an overshot

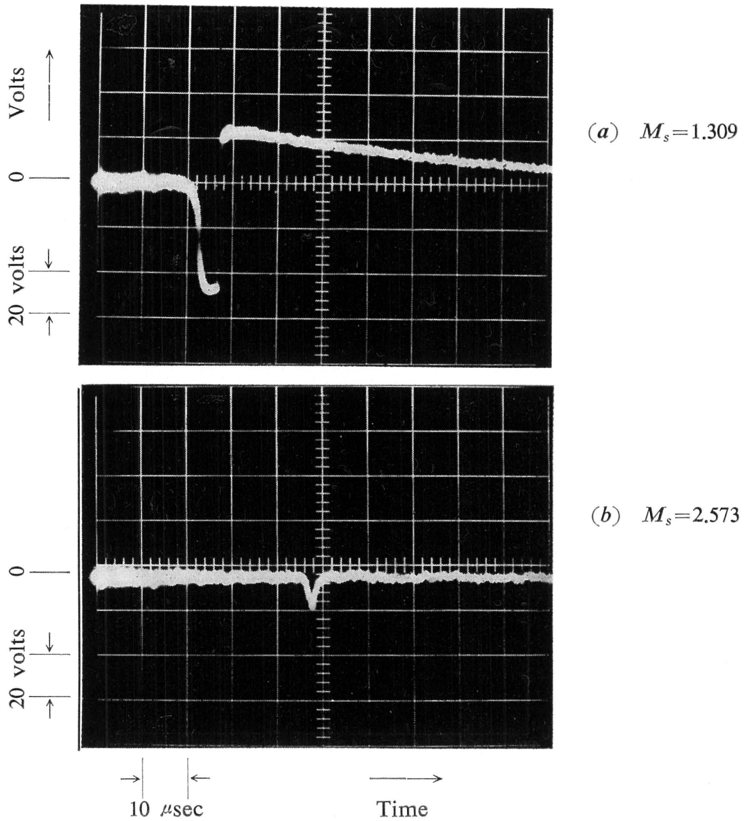


Fig. 22. Wave forms of pulses from the miniature schlieren system with pre-amplifier.
Conditions: load resistor=10 KΩ, $w_1=1.0$ mm, $w_2=1.2$ mm, $w_3=1.5$ mm, $|h|=0$ mm, light source =50 watts, $E_{phc}=-750$ volts.
Pre-amplifier with the cathode follower : frequency response=D.C.~4 Mc/s, gain=26±3 db.

was almost the same in all the experiments with various combinations of factors. This shock Mach number was about 2.4. On the inspection of Fig. 23, it becomes evident that the output voltage ΔV from the amplifier is a constant value of 50 volts up to $M_s \doteqdot 2.4$. Infering from these facts and the results that the input voltage into the wide band amplifier, as seen in Fig. 19, etc., is fairly a constant high voltage up to the order of $M_s=2.1$, we interpret that the amplifier arrives at saturation state for its input voltage out of the MS-9S up to $M_s \doteqdot 2.4$. Therefore, the amplifier works abnormally up to this value of M_s. It, however, works normally for the input voltage above $M_s=2.4$. The minimum value of the input voltage saturating this amplifier was over a range from 3 volts to 5 volts. This value nearly agrees with not only the value calculated from a saturation output voltage

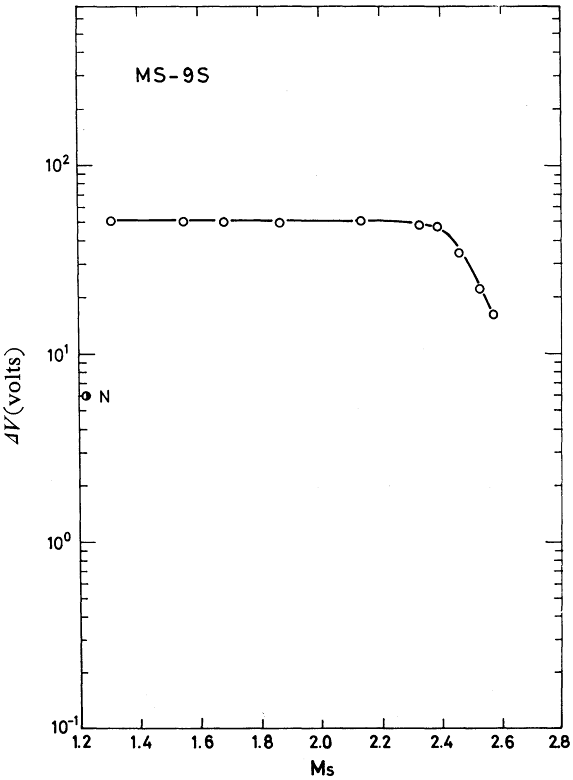


Fig. 23. Performance of the miniature schlieren system with pre-amplifier.
Conditions: load resistor=10 KΩ, w_1=1.0 mm, w_2=1.2 mm, w_3=1.5 mm, $|h|$=0 mm, light source =50 watts, $E_{phc}=-750$ volts, F_{nd}=2.38 μlm.
Pre-amplifier with the cathode follower: frequency response=D.C. ~4 Mc/s, gain=26±3 db.

of 50 volts and a gain of 26±3 db, but also the output voltage from the MS-9S at M_s=2.4 in Fig. 13, etc.

In the present experiments, as the input signal into the wide band amplifier varies over a wide range from 0.1 volts to 30 volts (see Figs. 11, 13, etc.), the amplifier works abnormally for the higher input voltage and the output signal is deformed. In order to make the amplifier normally work even if the input voltage is large, a wave shaping circuit for the input signal should be set up between the miniature schlieren system and the amplifier.

Now, the above conclusions may be summarized as the followings: a wide band amplifier is unnecessary when a trigger voltage of shock velocity measuring apparatuses (electronic counter, synchroscope, etc.) is sufficiently lower than an output voltage from the miniature schlieren system. In the present experiments, as the trigger voltage of the electronic counter is about ± 2 volts, the amplifier is indispensable for the measurements for a range of $M_s > 2.4$, but may be used when $M_s > 2.1$, at which ΔV from the photomultiplier is a little higher than this ± 2 volts, for the sake of an increase in reliability. For $M_s < 2.4$, the use of a wave shaping circuit is preferable.

3-2-12) *Results obtained*

For the present experimental apparatuses the followings may be concluded.
(1) The location of the slit S_3 on the optical-axis should be at the position of the image of the central plane of the test-section (see Fig. 1).
(2) The following values are optimum for dimensions of the slit S_1, S_2 and S_3, respectively.

S_1 :	1.0 mm width $\times$ 11 mm height.
S_2 :	0.5 mm $\times$ 11 mm $\sim$ 1.5 mm $\times$ 11 mm.
S_3 :	0.5 mm $\times$ 11 mm $\sim$ 1.5 mm $\times$ 11 mm.

(3) The blub used in the light source is most effective when it is lighted at its normal rating of 50 watts.
(4) There are not appreciable difference between the performances of the MS-9S and the 7696 if they are used for the shock tube. For the MS-9S, any load resistor 5 KΩ to 50 KΩ may be used without any practical trouble.
(5) The knife-edge of the slit S_2 must be so arranged as it agrees with the edge of the light source image and cuts off the light except diffracted and refracted rays. In such configulation, the colar of the image, on the slit S_3-plane, of the central plane of the test-section is nearly dark purple.
(6) The suitable service voltage for the MS-9S is over a range from -700 volts to -750 volts.
(7) For $|h| = 0$ mm, before or after the arrival of a shock wave to the center of the test-section, the appropriate quantities of the incident light flux F_{nd} into the MS-9S operating on $E_{phc} = -750$ volts are about 0.246 μlm$\sim$2.46 μlm, which do not saturate it.
(8) The present miniature schlieren system operates up to $M_s = 2.5 \sim 2.6$ with careful adjustment. For $M_s > 2.6$, $\Delta V/N$ shows the tendency to approach to a unity, so that the measurements of shock velocity may become uncertain or impossible. Therefore, it is thought that the upper limit of the shock Mach number up to which the present miniature schlieren system works may be a little higher than 2.6, or perhaps about 2.7.
(9) A wide band amplifier must be used when an output voltage from the miniature schlieren system becomes low. In our case, the amplifier are used for $M_s > 2.1$ for the sake of an increase in reliability. However, if these are used for the measurements for $M_s < 2.4$, the output wave is deformed and shows an overshot. For $M_s < 2.4$, the use of a wave shaping circuit is preferable.
(10) It is desirable that the upper limit of the frequency response of electric circuits used for the present apparatuses is about 8 Mc/s. This value can be calculated by knowing the width of the slit S_3 and the shock velocity to be

measured.
(11) The possibility that shock velocity may be measured only at one position ranging several millimerters is suggested.

The above-mentioned several results are of the miniature schlieren system used in this study. If the components, the focal length, etc. in a miniature schlieren system differ from one of our system, the different conclusions from ours may be obtained.

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