Development of High Speed Gas Gun with a New Trigger System

Hiroomi Homma[1], Hiroki Homma[2], Zakir Husin[3]

[1]Department of Mechanical Engineering, University of North Sumatera, Medan 20155, Indonesia

[2]Department of Mechanical Engineering, National Institute of Technology, Matsue College, Matsue, Japan,

[3]Graduate School of Mechanical Engineering, University of North Sumatera, Medan 20155, Indonesia

Abstract*—–*This paper reports development of a new trigger system for a high speed gas gun and experimental results on muzzle speed ofa spherical ceramic projectile launched by a gas gun equipped with the new trigger system. A new trigger system was designed carefully using numerical simulation of interaction between a trigger system and a projectile, and deformation of the trigger system. Launching pressure levels are precisely adjustable by changing trigger system parameters. Calculated launching pressure agreed well with experimental result. It was concluded that a gas gun equipped with this new trigger system can work out more powerful as compared with a commercial air rifle.

Keywords— gas gun, trigger system, silicon nitride ball, laser speed meter.

I. INTRODUCTION

A gas gun is widely used for researches on material property under high loading rate[1-3], new material creation having super properties[4], ballistic properties of material[5], armor material development[6] and so on. In aeronautic field, space dust impact onto space structures is one of critical issues for space development[7]. For this end, gas guns of which muzzle velocity are more than several kilometers per secondare developed. Recently, firearms development is accelerated and muzzle speed of a bullet launched from a firearm is more than 1 km per second[8]. Armor material and an armor vest must prevent a bullet from penetration to save life of the human who is shut by a firearm. Therefore, material properties under high velocity impact of 1 km/sec are enthusiasticallystudied.

Light gas guns are frequently used for researches on material properties and fracture mechanism under high velocity impact of more than 1 km per second. Those gas guns use a rupture disk for a trigger system. A rupture disk is placed between a reservoir and a barrel, and when pressure of the reservoir exceeds a critical level, the rupture disk is broken to propel a projectile in the barrel by swift flow of compressive gas from the reservoir behind the projectile. Thus, breaking pressure of a rupture disk dominates accuracy of projectile muzzle speed. Manufacturers carefully produce rupture disk so that scatter in breaking pressure of a rupture disk can be minimized. According to data sheets of one manufacturer of rupture disk [9], dispersion in breaking pressure of a rupture disk depends on a pressure level, and it is ±5% of target pressure. This means if a rupture disk is used for a trigger system of a gas gun, the launcher pressure varies 10% between the minimum and the maximum. When a rupture disk opens in a short moment by fracture of a thin material plate, propelling gas flows into a space behind a projectile through an opened mouth of the rupture disk. Therefore, rupture pressure does not suddenly push the projectile, but the pressure in the space behind the projectile quickly rises as a function of time. Therefore, the initial acceleration of the projectile sensitively depends on the rising pressure history, which is affected by fracture behaviors of the rupture disk. Reproducibility of experiments also depends on fracture behaviors the rupture disk. Namely, how fast does a rupture disk break and open fully.

To carry out excellent-reproducible experiments with a gas gun, a new trigger system of a gas gun must be developed. This work tries to develop a new trigger system and examines performance of the new trigger system.

II. DESIGN OF NEW TRIGGER SYSTEM

2.1 Basic Concept

Trigger systems developed or used for gas guns heretofore are classified into four categories, a mechanical valve system [10], an electro-magnetic valve system [11], a rupture disksystem [12], and explosive [13]. These triggersystems are placed between a reservoir and a barrel and make compressed gas in the reservoir flow into the barrel at a high velocity. Performance of a trigger system is strongly dependent on flow rate of compressed gas from a reservoir to a barrel. If the flow rate is low, a projectile cannot be fully accelerated. MarinaSeidl et al [14] indicate that if a gas gun is equipped with a mechanical valve trigger system, and a valve opening velocity is a certain value, a projectile muzzle velocity is lower than analytical prediction in which the infinitive opening velocity is postulated. In case of a mechanical valve trigger system, full valve opening time may be estimated several to tens milliseconds. An electro-magnetic valve trigger system takes a similar period to the mechanical one to open a valve fully. On the other hand, a rupture disk system fully opens within a period of 1 to 5 msec, or 15 to 20 msec. In general, many researchers believe that a rupture disk can open fully more rapidly than the other trigger systems. Therefore, a rupture disk is used for a trigger system in many hypervelocity gas guns.

As mentioned by Marina Seidl et al [14], valve opening time has a significant and negative effect on a muzzle velocity of a gas gun projectile. A new trigger system must be developed so that the valve opening time is reduced to zero.

2.2 A New Trigger System

In order to reduce a valve opening period of a trigger system to zero, a projectile is fixed in a projectile trap and directly subjected to application of compressed gas from a reservoir as shown in Fig. 1. The pressure of the reservoir is gradually increased until the projectile has been extruded through the projectile trap.

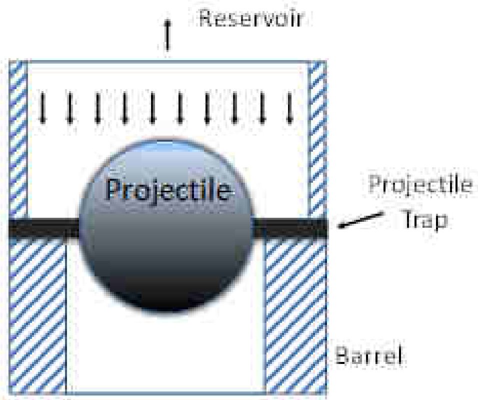


Fig. 1:Basic idea of a new trigger system for gas gun

The projectile trap has two functions, sealing between a reservoir and a barrel, and adjustment of launching pressure of a gas gun. Material used for a projectile trap must possess several properties such as:

- Low elasticity as compared with metallic material for sealing

- Large elongation to fracture to pass a projectile through a trap without any catastrophic failure
- Anti-abrasion against sliding

To adjust launching pressure, appropriate dimensions must be determined. In the next sections, material selection and decision of the dimensions are discussed.

2.3 Material selection

Material selection is crucial to develop a new trigger system. Considering the properties to be possessed by a projectile trap material mentioned above, several potential materials were selected from plastic materials having excellent sliding properties and shown in Table 1. In the table, mechanical properties are also indicated.

Table.1: Potential materials for projectile trap

Material	POM	PET	PFTE	PAI
Young's Modulus GPa	3.1-3.6	2.8-4.2	0.4-0.6	4.5-18.6
Tensile Strength MPa	3.1-3.6	48-73	20-35	81-221
Elongation %	25-75	30-300	200-400	6-35
Coefficient of Friction	0.18	0.25	0.1	0.15-0.31

POM (polyoxymethylene), PET (polyethylene terephthalate), PFTE (polytetrafluoroethylene), PAI (polyamide-imide)

Above three materials, POM, PET, PFTE, satisfy some of the properties mentioned above, but their tensile strength and Young's modulus are much lower than those of PAI.

To accelerate a projectile at a high velocity of more than 900 m/sec, launching pressure of a gas gun must be higher than 10 MPa. Therefore, a projectile trap must be stiff and tough to hold a projectile under such high pressure. In this work, PAI was selected for the trap material. There are many kinds of PAI products. Torlon is one of PAI products developed by Solvay Specialty Polymer and is widely supplied in the market. This work adopted Torlon 4203L as a projectile trap material because of high Young's modulus, 4.5 GPa, high tensile strength, 190 MPa, and moderate elongation, 15%.

2.4 Analysis description to determine a projectile trap dimensions

In this work, a projectile was a silicon nitride sphere used for ceramic ball bearing of which diameter is 6.0±0.00013 mm (JIS Grade 3). While considering the projectile shape, a projectile trap may have geometry of a center-holed disk. The trap disk thickness and the center hole geometrywere determined based on numerical analysis of launching, namely extrusion of a projectile from a trap disk. Numerical analysis of the extrusion was carried out using ANSYS Multiphysics ver.13. Anumerical model is shown in Fig. 2.

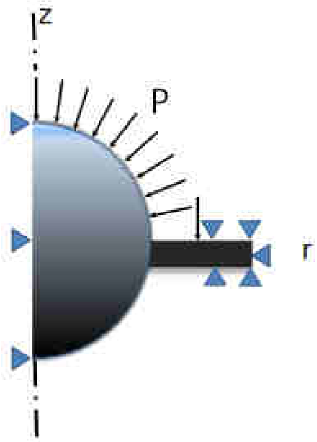


Fig. 2: Numerical analysis model

According toaxi-symmetry, a half of the modelwas used for axi-symmetric analysis. Along a center line of the model, displacement of the projectile was fixed in r direction, and the upper surface of the projectile was subjected to pressure. A projectile trap was fixed in z direction and r direction near the end of trap. The pressure was gradually increased until the projectile was extruded, and deformation and stress in the projectile trap were calculated. Contact surface between the projectile and the trap was treated as a friction surface. As the projectile surface was subjected to pressure, the projectile trap was subjected to compression and bending due to downward displacement of the projectile. In the initial condition, the projectile was placed on the center hole of the trap and the contact circle wasbelow its equator. When the projectile sliddownward, the contact circle approached its equator to enlarge. Eventually, application of the pressure to the projectile resultedin compressing the trap.Because Young's modulus of the projectile material was hundreds times larger than that of the trap material, the projectile deformed negligibly as compared with the trap. In addition, when the projectile slid downward, friction force was generated between the projectile and the trap tobend the trap.When the trap was bent, the hole diameter of the trap enlarged to extrude the projectile.Launching pressure strongly depended on the center hole diameter and the thickness of the trap. To obtain the launching pressure in range of 0.1 to 12 MPa, the trap dimensions were decided by the numerical analysis.

2.5 Conditions of numerical analysis and calculation results

Mechanical properties of materials, silicon nitride and PAI Torlon 4203L used for the numerical analysis are summarized in Table 2.

Table.2: Mechanical Properties of materials

Materials	*Young's Modulus GPa*	*Tensile Strength MPa*	*Poisson Ratio*	*Coefficient of Friction*
Si_3N_4	*290*	*550*	*0.28*	*-*
Torlon 4203L	*4.5*	*152 (244)*	*-*	*0.5-0.31*

Torlon4302L is PAI for general use. According to data sheet provided by Solvay Specialty Polymer, Torlon does not yield at room temperature and stress-strain relation is provided in the data sheet as shown inFig. 3. In this analysis, Torlon 4203L was considered a incompressive hyper-elastic material and its stress strain relation was expressed by 5-parameter

Mooney-Rivlinmodel through ANSYS Material Models option, because 5-parameter Mooney-Rivlin model gave a good approximation with a residual of less than 0.06 Pa for stress against the experimental data shown in Fig.3.

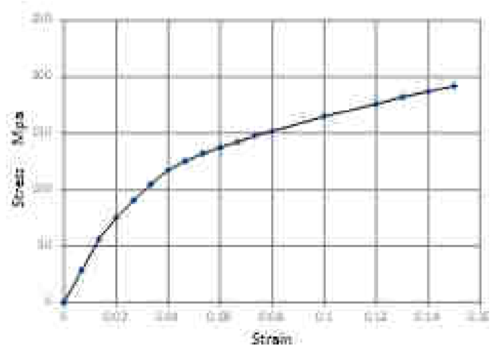
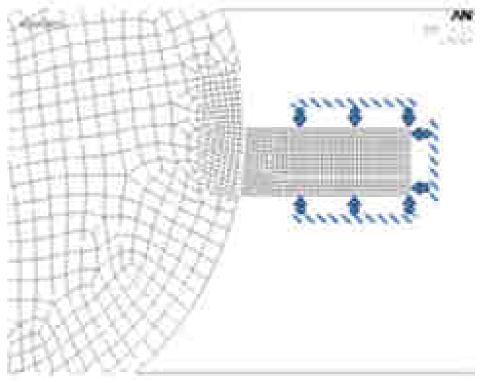


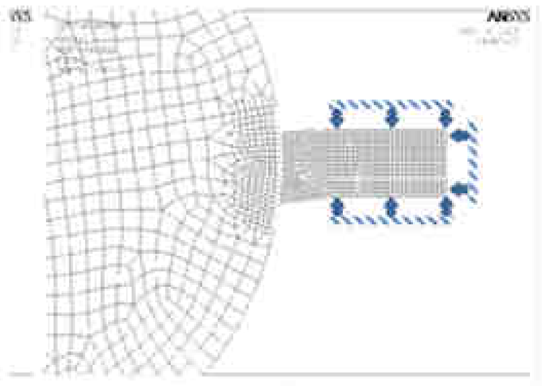
Fig. 3: Stress-strain curve of Torlon 4203L

Coefficient of friction may be one of crucial parameters influencing launching pressure.The coefficient of friction varies from 0.15 to 0.31 depending on the normal pressure. In general, coefficient of friction varies by combination of contacting materials, surface roughness, temperature, and lubricants. It is out of this research scope to determine a precise coefficient of friction between Torlon 4203L and silicon nitride sphere,the coefficient of friction was assumed constant, 0.25 for this numerical analysis.

Fig. 4 shows a numerical analysis results at the initial stage and just before launching.In (a), initial stage before application of pressure is shown and in (b), appearances of a projectile and a projectile trap just before launching are shown. The projectile slides down by 0.16 mm and a projectile trap is bent. When relative positions of meshes in the projectile and the trap are traced, it can be seen obviously that slip between the projectile and the trap takes place.

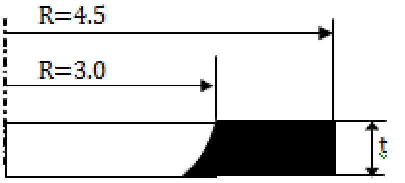


(a) Initial stage

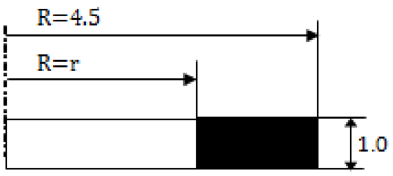


(b) Launching stage

Fig.4: Deformation of a projectile trap at launching stage

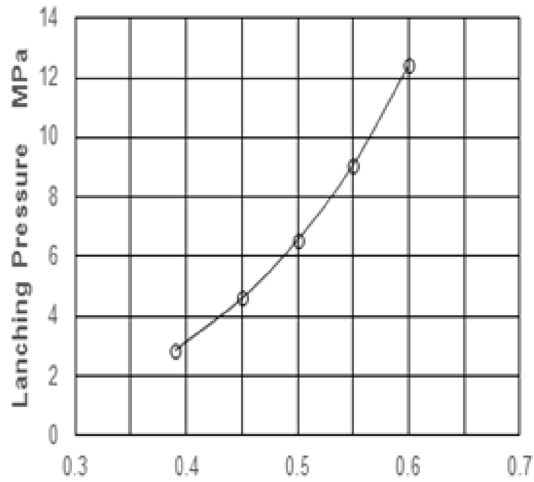


(a) fitting hole

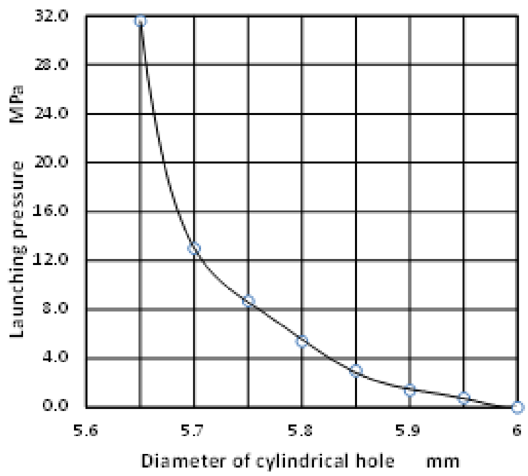


(b) cylindrical hole

Fig. 5: Configurations of trap hole



(a) Fitting hole



(b) Cylindrical hole

Fig. 6: Calculated launching pressure for both hole configurations of trap

Two configurations were considered for a center hole of a trap as shown in Fig. 5. One was the configuration shown in Fig. 4 that has the same longitudinal surface profile as that of the spherical project to smoothly contact with the projectile along the thickness. The other one was a cylindrical hole with a certain diameter for easy machining. In a fitting hole, a spherical projectile sunk in the hole up to its equator. In this case, trap thickness was a parameter to determine the trap dimensions. On the other hand, the trap thickness was fixed at 1.0 mm, and diameter of cylindrical hole was varied.

For both center hole configurations, launching pressure (gage pressure) was obtained for several trap thickness. In Fig. 6, calculated launching pressure is plotted as a function of the trap thickness and the hole diameter for both the hole configurations. As shown in the Fig., the launching pressure of a gas gun can be adjusted by change of trap thickness or trap hole diameter. It should be noted from the calculation result shown in the Fig. that the launching pressure can be provided from commercial high pressure gas cylinder, such as nitrogen gas and helium gas of which the maximum charging pressure is 15 to 25 MPa.

III. EXPERIMENT OF A NEW TRIGGER SYSTEM FOR VERIFICATION

Launching experiment of a gas gun equipped with a new trigger system was carried out. A stainless steel barrel for an air rifle of which dimensions are 6.08 mm in inner diameter, and 650 mm in length, was utilized for the gas gun. Projectile was a silicon nitride ball used for a ball bearing, and its nominal diameter is 6.0±0.00013 mm, JIS 3rd grade for ceramic sphere. Nitrogen gas was used for a propellant gas. Two photodiodes connected in series and two 20 mW laser beams were used to measure muzzle velocity of a projectile.

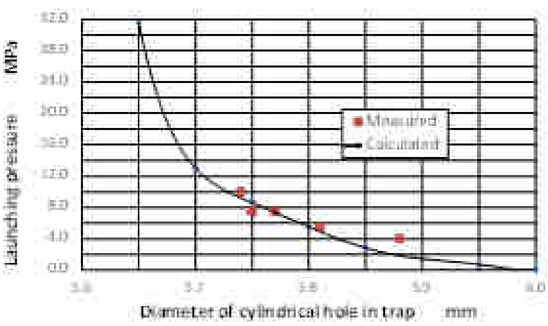


Fig. 7: Measured launching pressure

In the experiment, traps with a cylindrical hole were used for a trigger system. In Fig. 7, measured launching gage pressure (gage pressure) is plotted as a function of cylindrical hole diameter being compared with the calculated results.

The measured launching pressure results reasonably agree with the calculated results, but they are slightly higher than the later. The discrepancy may be caused by the calculation conditions, especially coefficient of friction, constraints of trap fixture. If the calculation conditions are improved to reflect actual situations, the measured and the calculated launching pressure may more crossly agree with each other.

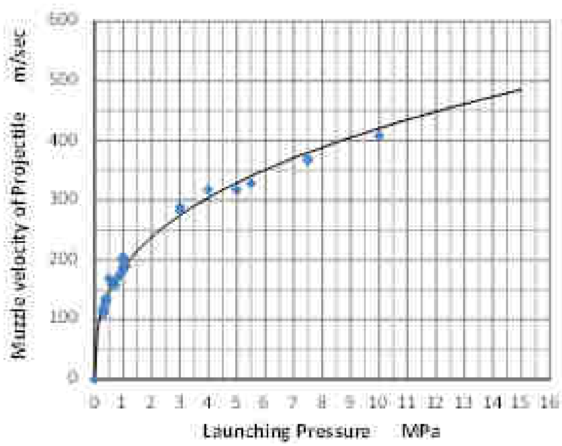


Fig. 8: Muzzle velocity of projectile

In the experiment, muzzle velocity of the projectile was measured by use of a photo diode-laser measuring system. The muzzle velocity is plotted as a function of launching pressure in Fig. 8. Experimental data are slightly deviated, but deviation band is quite narrow. Using nitrogen gas pressurized up to 10 MPa (gage pressure), and a 650 mm long barrel, a silicon nitride spherical projectile with a diameter of 6.0 mm was accelerated to 408.1 m/sec.

IV. DISCUSSION

As shown in Fig. 7, a new trigger system using a projectile trap launched a projectiles expected from the numerical analysis. The close comparison between experimental results and numerical results indicated that the measured launching pressure was always higher than the calculated one. There are several reasons to be considered for this discrepancy. Machining precision of cylindrical hole trap was ±0.02 mm. The machining precision effect is trivial for the discrepancy. In the numerical analysis, some simplifications were made. As mentioned in Fig. 4, displacements of trap end was fixed in z direction or r direction in the trap fixture in case of a fitting hole trap. In addition, it should be noted that in case of a fitting hole trap, bending mode was dominant in the trap deformation. On the other hand, in a cylindrical hole trap, the hole expansion in r direction, compression mode was dominant in the trap deformation as shown in Fig. 9, because of 1 mm thickness. Therefore, displacement of the trap end in r direction takes a dominant effect on launching pressure. The diameter of the trap fixture is slightly larger than the trap diameter. Therefore, the trap can deform in r direction in the trap fixture even though it is very small, 10s microns. The numerical calculation does not take into account friction between the trap surfaces and trap fixture and displacement constrain in r direction at the trap end. This may result in low launching pressure.

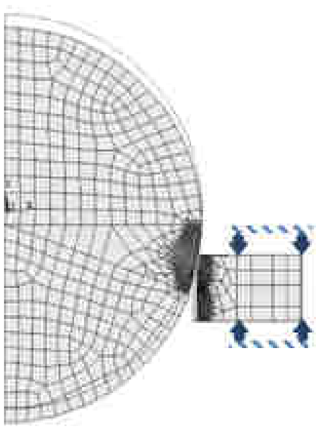


Fig. 9: Deformation ofcylindrical hole trap

As mentioned in Fig. 8, muzzle velocity of the gas gun using nitrogen gas as a propellant gas increased with launching pressure. At the launching pressure of 10 MPa, which is almost equal to the maximum charging pressure of high pressure gas cylinder, the muzzle velocity reached 408.1 m/sec. Because the silicon nitride sphere has mass of 3.62×10^{-4} kg, the kinetic energy of the projectile is 30.1 Nm(J).

For comparison, one example is taken from a commercial air rifle. Benjamin Discovery has 5.6 mm (0.22 inches) wide caliber and 616 mm (24.25 inches) long barrel [15]. When this air rifle charged by CO_2 gas compressed to 13.8 MPa (2000 psi)is fired, the rifle works out around 35.0 J (26 f lbs).

In this research, the gas gun was charged by N_2 gas compressed to 10.0 MPa, at the highest. To extrapolate a muzzle velocity under launching pressure of 13.8 MPa, a curve fitting method was used together with the least square method. A curve to be fitted to the experimental data is expressed as

$$v = 186.3P^{0.35} \qquad (1)$$

In Fig. 8, the obtained curve is shown with a solid line. As seen in the Fig., the curve excellently represents the experimental data. From Equation (1), muzzle velocity under launching pressure of 13.8 MPa is estimated as

v = 483.1 m/sec

Eventually, this air gun charged with N_2 gas compressed to 13.8 MPa works out 45.4 Nm (J). As compared with the commercial air rifle, the gas gun developed in this research is 1.3 times powerful. Of course, it should be noted that propellant gases were different in both.

V. CONCLUSIONS

To eliminate losses caused by periods of a trigger valve opening, and propellant gas arrival from reservoir to a projectile back surface, a new trigger system was developed in this work. The new trigger system consisted of a projectile trap and a projectile. The projectile trap and the projectile functioned as a sealing between a gas reservoir and a gun barrel before launching. Two types of projectile trapswere proposed, a fitting hole trap and a cylindrical hole trap. In a fitting hole trap, launching pressure was increased up to more than 10 MPa with trap thickness, while in a cylindrical hole trap, it was increased as a hole diameter was deceased. This new trigger system was installed to a gas gun that was constructed by 650 mm long barrel for an air rifle. A silicon nitride sphere with diameter of 6.0 mm was launched from the gas gun to measure muzzle velocity of a projectile to evaluate the new trigger system. The following conclusions were obtained:

1. A new trigger system could work well as designed.
2. Air gun with the new trigger system worked out 45.4 Nm (J) for muzzle kinetic energy, which is around 1.3 times powerful than one of the most powerful commercial air rifles.
3. To precisely design a projectile trap for a desired launching pressure, more precise calculation conditions must be taken into account.

It can be easily expected that if a longer barrel and compressed helium gas as a propellant are used for the gas gun, the muzzle velocity is increased up to 1000 m/sec.

If a more appropriate material for a projectile trap is found, it may be possible to develop more powerful gas gun.

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