Free-Flight Testing in the Gas-Driven Two-Stage Light Gas Gun HEK-G

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(Received June 24th, 2011)

The current status of free-flight testing with the gas driven two-stage light gas gun in JAXA Kakuda was reported. Modifications of the gun were followings. (1) Maximum pressure of the pump tube end section was increased from 100MPa to 200MPa, (2) Test section for 15mm gun barrel was extended from 5m to 6.5m with an additional optical windows located at the test section, (3) 4-pieces sabot for 15mm diameter gun barrel (4) High-speed video camera and high-wattage light source. (5) Newly built 72mm diameter gun barrel for 50mm diameter projectiles and (6) 2-pieces sabot for 72mm diameter gun barrel. The 15mm diameter gun barrel was going to be used for the study for aerodynamics under hypersonic condition. The 72mm diameter gun barrel was going to be used for the study on the aerodynamic instability of re-entry capsules under transonic to supersonic condition. In a test campaign with the 15mm diameter gun barrel, we have launched 5mm diameter sphere projectiles with 4-pieces sabot at a velocity at the gun barrel muzzle of 2.1km/s to 3.8km/s. We successfully observed sabot separation and projectile (5mm diameter steel sphere) release through the high-speed video camera. In a test campaign with the 72mm diameter gun barrel, we successfully conducted to launch Apollo shaped capsule projectile of 50mm diameter with 2-pieces sabot at a velocity at the gun barrel muzzle was approximately 430m/s. Our in-housed quasi-one-dimensional Navier-Stokes code was applied to determine safety operation condition of the 72mm gun barrel and to estimate projectile speed.

Key Words: Ballistic Range, Two-Stage Light Gas Gun, Free-Flight

1. Introduction

Since 2007, JAXA started to research on aero-ballistic range for the purpose of free-flight ground test¹⁾. A free-piston shock tunnel HEK (High Enthalpy shock tunnel in Kakuda) in JAXA was modified to the gas driven two-stage light gas gun HEK-G. The major feature of this facility is the free-piston driver, which enables the driver piston fully reusable, resulting to the low cost and short turn-round operation. For the performance prediction and design of the facility, a quasi-one dimensional Navier-Stokes code was applied to simulate gas-dynamics with piston and projectile motion. The gun has mainly focused to produce free-flight aerodynamic data as a benchmark to evaluate wind tunnels and numerical simulations.

In the fiscal year 2010, we upgraded several points of the facility. Since aerodynamic instability of capsule shapes under transonic flow becomes important technical issue in JAXA, we modified the gun mainly for transonic testing with larger projectiles. The latest test results obtained with the upgraded HEK-G were reported in this paper.

2. Upgrade of the Two-Stage Light Gas Gun HEK-G

As already reported in the previous paper¹⁾, the two-stage light gas gun HEK-G was a facility modified from the high-enthalpy shock tunnel HEK²⁾. Since HEK was originally built as free-piston shock tunnel, which driver produces high-pressure and high-temperature helium gas through adiabatic compression process with a heavy piston, HEK-G also has the remarkable feature as the followings.

(1) Fully reusable piston: This feature will shorten the turn round time to re-set up the facility. The operation cost can also be reduced accordingly.

- (2) No gun-powder: Low erosion rate of the pump tube. Un-necessity of special equipment and permission (Japanese domestic regulation) to handling of gun powder.
- (3) Wide operation envelope: Pump tube pressure can be varied from 2MPa to 200MPa. It can allow flexibility to adjust operation condition for different mass projectile under required launch velocity.

A test campaign in FY2010, we upgraded HEK-G as the shown in the below.

- (1) High-pressure pump tube: Pump tube pressure 100MPa to 200MPa.
- (2) Extended test section and an additional optical window: Test section was extended to 5m to 6.5m for the installation of target plate holder. Number of optical window was increased from three stations to four stations.
- (3) 4-pieces sabot for the 15mm diameter gun barrel: In order to launch steel bearing for high-speed impact testing into test plates.
- (4) High-speed video camera (SHIMAZU Hypervision) and high-wattage light source.
- (5) Newly built 72mm bore gun barrel: For the purpose of the aerodynamic test with re-entry capsules.
- (6) 2-pieces sabot for the 72mm diameter gun barrel.

The 72mm diameter gun barrel was built for the purpose of the free-flight tests to measure aerodynamic instability of re-entry capsules at transonic to supersonic speed. Since the HEK free-piston driver was originally designed for 72mm diameter gun barrel (Shock tube), we expected that the driver can operate ideal condition. In Fig.1, the schematics and a photograph of the newly built 72mm bore gun barrel were shown. The gun barrel was made of 18-8 stainless steel (SUS-304), which length was 2.5m. In order to avoid effects of shock waves reflection from the test section wall, the projectile is going to be launched

into open test space instead of the closed test section. The length of the free-flight measurement section was 2.5m. Finally, the projectile is going to be caught by projectile catcher, which was a boxed structure made from two layers of poly-urethane forms, five layers of Kevlar sheets and bread-board (shown as Fig.2).

Fig.1. 72mm bore newly built gun barrel for transonic free-flight test.

Fig.2. Projectile recovery box. Five layers of yellow Kevlar sheets and poly-urethane forms were located to mitigate projectile damage.

3. Numerical Simulation

The numerical code used in this study was quasi one-dimensional Navier-Stokes finite differential code based on 2nd order KRC scheme³⁾. In the preliminary test campaign in the last FY, we already verified the code can accurately predict the safety operation conditions for HEK-G with 15mm bore gun barrel. In this test campaign, numerical calculation was conducted to determine safety operation condition with the 72mm gun barrel.

For safety operation and fully reusable piston, it is essential to achieve soft landing piston at the end of pump tube. As already described above, the original driver of HEK was applied in

this study, the air reservoir and the pump tube dimension was fixed. Hence, the adjustable parameters to control the operation condition are the secondary reservoir initial pressure the pump tube initial pressure and piston mass.

Since the purpose of 72mm bore gun barrel was for the aerodynamic testing with reentry capsules under transonic to supersonic speed, pump tube condition (pressure) must be quite lower than original design. For the transonic speed with 260g projectile, the rupture pressure of main diaphragm was 2MPa. Secondary reservoir pressure was 0.2MPa accordingly. In FY2010, the maximum pressure of the pump tube in the HEK was increased from 100MPa to 200MPa, the rupture pressure of the main diaphragm was hence extremely out of standard operation condition. As shown in the Fig.3 (top figure), pump tube pressure should be above main diaphragm burst pressure (2MPa). Piston soft landing condition was also evaluated with the piston trajectory as shown in the middle of the figure. As shown in the bottom of the figure, we adjust the secondary reservoir initial pressure and pump tube initial pressure to achieve the projectile speed approximately Mach 1.4 (420m/s). Operation condition was finally decided as shown in the Table.1.

Fig.3. Numerical simulation results to tune the operation condition for 72mm bore gun barrel. (top)Pump tube pressure history, (middle)piston trajectory and (bottom)projectile trajectory were shown.

Table.1 Test condition of HEK-G with 72mm bore gun barrel.

<i>Secondary reservoir pressure (MPa)</i>	0.35
<i>Piston mass (kg)</i>	25.7
<i>Pump tube (Pump tube) initial pressure (kPa)</i>	12
<i>diaphragm rupture pressure (MPa)</i>	2
<i>Gun barrel length (m)</i>	2
<i>Projectile mass (g)</i>	260

4. Results

4.1. 15mm gun barrel

With the 15mm diameter gun barrel, 5mm diameter steel spheres (steel bearing, mass 5g. shown in the Fig.4) were used as projectiles. In the 15mm gun barrel test campaign in this FY2010, main purpose was the verification of a prototype sabot. Operation condition of the pump tube was hence fixed to the condition determined in the test campaign last year (shown in table 2). To measure projectile speed, two set of lasers and photo-detectors were instrumented as shown in Fig.5 (top). Laser 1 was located at the exit of the gun barrel, while Laser 2 was located 445mm behind the Laser 1 position. Projectile speed was calculated with time of flight measured from these two photo-detector outputs. One of the photo-detectors outputs were also used as the trigger signal for the high-speed video camera. The high-speed video image (Fig.6) showed that the projectile was successfully released from the 4-pieces sabot. Through the test campaign, test section pressure was changed from 1kPa to 10kPa to observe aerodynamic effect on sabot separation. Sabot separation was also clearly shown as footprints on the target plates shown in the Fig.6. The hole in the middle of the each plate was the projectile penetration.

Fig.4. 5mm steel sphere installed in 4-pieces sabot.

Table.2 Test condition of HEK-G with 15mm bore gun barrel.

<i>Secondary reservoir pressure (MPa)</i>	1.1
<i>Piston mass (kg)</i>	25.7
<i>Pump tube (Pump tube) initial pressure (kPa)</i>	45
<i>diaphragm rupture pressure (MPa)</i>	10
<i>Gun barrel length (m)</i>	4
<i>Projectile mass (g)</i>	6

4.2. 72mm gun barrel

In the beginning of the present test campaign with 72mm diameter gun barrel, system check of this newly built gun barrel was conducted. The free-piston driver was operated under the condition as already shown in Table 1, which was decided by the numerical prediction code. Through the test campaign, we successfully operated the facility without any damage on the facility (includes free-piston and piston buffer at the end of

Fig.5. Lunch tube and test section of the gun. Two sets of lasers and detectors were instrumented to measure projectile speed. Top: setup for the 15mm gun barrel. Bottom: setup for the 72mm gun barrel.

Fig.6. An example of high-speed video image. Projectile was flying from right to left at 1.5km/s.

pump tube). As already described, the projectile was launched into open space.

Top picture of Fig.8 showed Apollo shaped projectile, 2-pieces sabot and retainer ring. The retainer ring holds the sabot so as not to separate before it launch from the muzzle. Bottom picture of Fig.7 showed the example of high-speed video image. The picture clearly indicated the sabot and retainer ring successfully

Fig. 7. Test plates (mild steel JIS SS400) after shot.

Fig.8. Top: An Apollo shaped projectile, 2-pieces sabot and retainer ring. The retainer ring hold 2-pieces sabot in the launch tube. Bottom: Example of high-speed video image. Sabot and retainer ring was successfully separated from the Apollo shaped projectile. Flight velocity of the projectile was 0.43km/s.

Fig.9. Apollo shaped projectile recovered from the shot.

Fig.10. Example of laser detectors outputs. Each laser clearly detected Apollo shaped projectile. Projectile speed 428m/s was obtained from this measurement.

separate from the projectile. With the soft landing system, which was made of Kevlar sheets and urethane forms, the projectile was recovered without any damages after the shot (as shown in Fig.9).

Projectile speed was measured through the same instrumentation used for the 15mm gun barrel. Fig.10 showed the example of the laser detector outputs. Measuring time difference between each laser outputs, projectile speed was calculated as shown in the table 3. It should be noted that measured projectile speed was slightly faster than that of predicted by numerical simulation. It means that gas-dynamic or mechanical loss of the 72mm gun barrel was negligible. This result was quite different from the results with 15mm gun barrel we obtained in the last year, which results showed gas-dynamic and mechanical loss was approximately 40%. We believed that this high-efficiency was caused by the following reasons.

(1) Cross section ration between launch tube (210mm diameter) and gun barrel (72mm diameter) was approximately 1/9, which was thought as an optimum ratio for free-piston driver. Low gas-dynamic loss was hence obtained with this original designed dimension for HEK.

(2) Low compression ratio for the quite low launch tube pressure (less than 3MPa). To obtain quite low lunch tube pressure,

Fig.11. Top: An Apollo shaped projectile for the study on transonic instability of reentry capsules. Bottom: Prototype of the projectile-onboard miniature data logger. Size of the logger is 65mm diameter and 60mm height.

Table 3. Comparison of projectile speed measured and predicted

<i>Projectile speed measured</i>	428m/s
<i>Projectile speed predicted</i>	420m/s

compression ratio of this operation condition was almost 20, which was the minimum compression ratio for the operation of the free-piston driver. Heat loss in the compression process was thus reduced compared with usual free-piston driver operation, which usual compression ratio is approximately 50.

5. Future Plan - Aerodynamic Instability Test -

For the measurement of aerodynamic instability with reentry capsule models, we are going to use projectiles in which miniature onboard data-logger instrumented. Since the prototype data-logger became bigger than we expected, bore of the gun-barrel is going to increase from 72mm to 120mm. The design of the 120mm gun barrel was already finished and performance was evaluated with the quasi-one dimensional numerical code. The projectile going to be use in the study was shown in the upper picture of Fig.10(top figure). The projectile was made of A7075. After the flight test, the model is going to be recovered and reused. Bottom of the Fig.10, prototype of the data-logger was shown. The logger has miniature accelerometers and gyros. It is a standalone measurement system, which can measure 10-channels for 500ms duration. The logger was design to be shock resistive. Free-flight test with the system was expected in

June or July 2011.

Acknowledgments

The authors wish to thank to Mr. Mehara, Mr.Narita and Mr. Fujimura who operate the facility.

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