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Performance Optimization of Hypervelocity Launcher System using Experimental Data

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This study presents the performance optimization of hypervelocity launcher system by using the experimentall data. During the optimization, the RSM (Response Surface Method) is adopted to find the operating parameters that could maximize the projectile speed. To construct a reliable response surface model, 3 full factorial method is used with the selected design variables, such as piston mass and 2 driver fill pressure. Nine test data could successfully construct the reasonable response surface, which used to yield the optimal operational conditions of the system using the genetic algorithm. The optimization results are confirmed by the experimental test with a good accuracy. Thus, the optimization can improve the performance of the facility.

Key Words : Hypervelocity Launcher System, Numerical Optimization Response Surface Method, Genetic Algorithm

1. Introduction

Hypervelocity Launcher System (HLS) is the one of the experimental facility to study hypersonic speed projectile. HLS consists of two separate stages. Those are the driving part and the driven part classified by the role of high pressure gas. Seigel (Arnold, 1978) is one of the pioneer who invented the initial concept of the system. Crozier (Lukasiewicz, 1973) and Humes had extended the initial concept by building hypervelocity launcher with modifications from Mines Gun in 1948. Since then, many similar types of gas gun has been constructed and tested to have better performances. In other aspects, Bogdanoff (1996) has presented the optimization of performance of hypervelocity launching system in 1996. He used CFD tool to find the sensitivity of each design variable for the overall performance. And the optimization result was confirmed by experimental tests. CFD shows its capability in predicting the overall performance and the sensitivity of each design variable as well. However, CFD works seem to take a tremendous amount of computational time and efforts to optimize the hypervelocity launching system because of an intrinsic complexity of the computation of this system. Thus, it is natural to seek a relatively convenient and efficient method of optimizing the hypervelocity system.

In this study, optimization of the overall performance is processed with experimentall data that could be used to construct the response surface in the design plane. The objective function is the speed of projectile and design variables are chosen to implement their influence on the objective function. It should be noted that the biggest advantage of the method adopted in this study is to reduce time and effort in finding the optimal operational condition by constructing the response surface with test data.

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In addition, it is of importance to decide the number of tests required for constructing response surface. The method of 3^k full factorial is the one used in this study that could yield an approximate response surface on which the influence of each design variable could be assessed. And the code used for optimization is GENOCOP III, an intrinsic GA algorithm. After the construction of response surface of design variables, the optimization process with GENECOP III is performed to find the optimal operational conditions. It is believed that this optimization process with an approximate response surface could improve the conventional technique that utilized only expert's experiences and would be extended to similar problems.

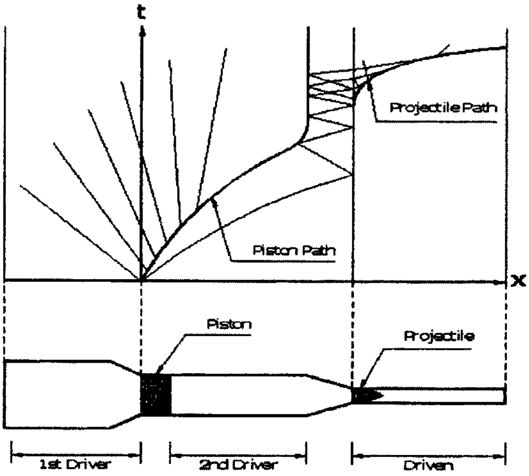


Fig. 1 Wave diagram of flow in a hypervelocity launcher

2. Experimental Facility

The problem defined in this study is the optimization of overall performance of hypervelocity launcher system. Generally, two stage gas gun is one of the typical experimental facilities for this purpose. Thus, the optimization has been attempted with two stage gas gun in this study. Two-stage gas gun consists of the first driver, the second driver (pump tube), and the driven part. Figure 1 shows the schematic of the general two-stage gas gun and an idealized wave diagram. As the piston is accelerated by the expansion of the first-stage propellant, the energy of the piston in the second driver can be transformed into high pressure in the chamber located in front of the piston. And this causes to rupture the diaphragm at the far downstream of the second driver. And the projectile is launched to a hypervelocity speed as a consequence of the rupture of diaphragm.

Figure 2 and 3 show the components and dimensions of hypervelocity launcher developed in 1998 and located at the Department of Aerospace Engineering of the Konkuk University.

The diaphragm is picked up with polyester film (50-300μm) and stainless steel (SUS304: 1.0 mm), which has higher rupture strength and produces fewer broken pieces. Figure 4 shows

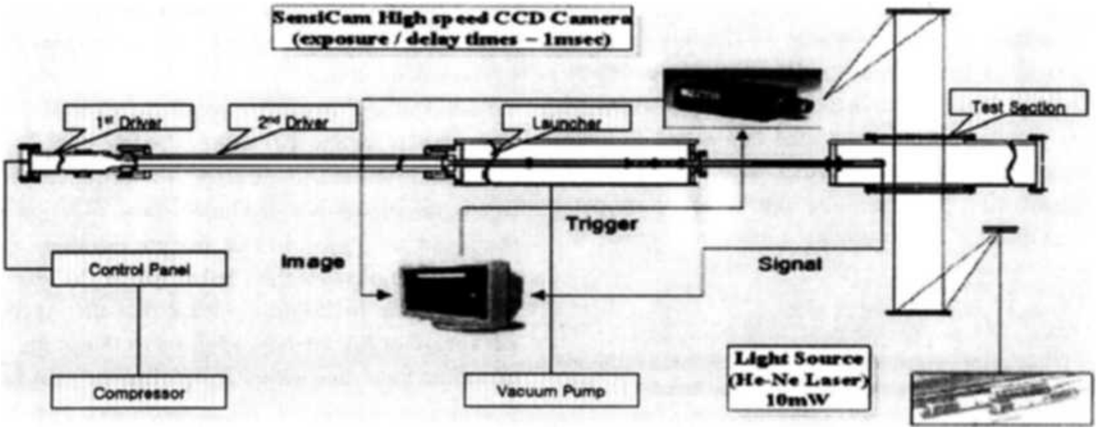
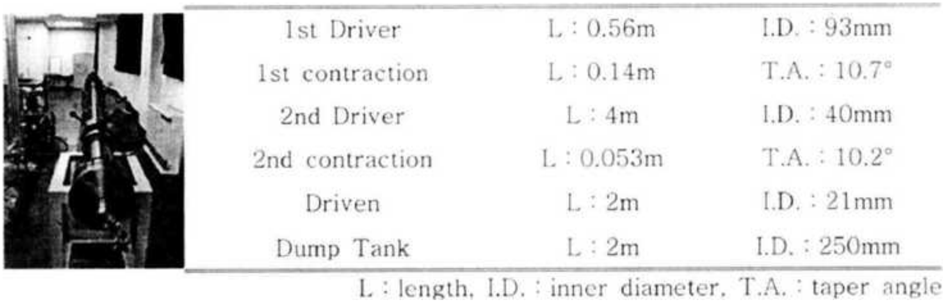


Fig. 2 Components of the Konkuk University hypervelocity launcher



1st Driver	L : 0.56m	I.D. : 93mm
1st contraction	L : 0.14m	T.A. : 10.7°
2nd Driver	L : 4m	I.D. : 40mm
2nd contraction	L : 0.053m	T.A. : 10.2°
Driven	L : 2m	I.D. : 21mm
Dump Tank	L : 2m	I.D. : 250mm

L : length, I.D. : inner diameter, T.A. : taper angle

Fig. 3 Dimensions of the Konkuk University hypervelocity launcher

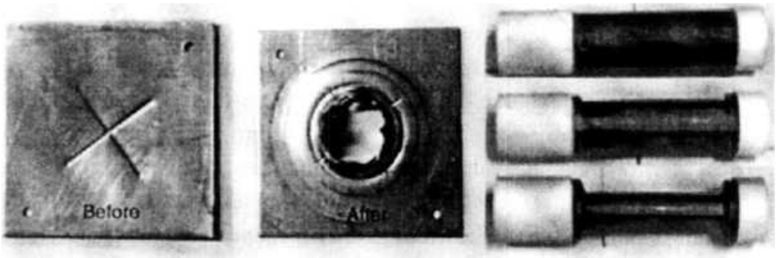


Fig. 4 Pictures of diaphragm before rupture, diaphragm after rupture and piston

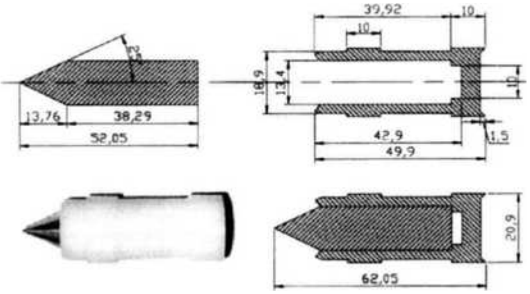


Fig. 5 Projectile used in this experiment

stainless steel diaphragm ; 60×60mm in size and 1.0mm thickness, ruptured diaphragm and pistons of different mass respectively. MTS (Material Test System) is used for making a groove on the stainless steel diaphragm.

The piston is made with 3 parts : the head, body and tail. The head and the tail are made of Teflon, which can reduce friction and keeps the second-stage driver airtight.

Furthermore, Teflon has many advantages in manufacturing and shows a very good heat-resistant property as well. The piston body is made of a brass and a steel (S45C) with different mass ratio. Figure 5 shows the projectile shape used in the experiments. The contact area of projectile is determined to reduce the friction to a wall and its weight is 29.6g. The projectile is composed of duralumin main body and acetal sabot.

3. Experimental Methods and Performance Parameters

It is worthy noting that the overall performance depends on many parameters of the system such as piston mass, length of driven part, pipe diameter, fill pressure, etc. However, it is difficult to include every performance parameters in designing the optimal operation condition and only a few parameters can be substantially varied in the optimization process if the facility was designed and constructed physically. This study, therefore, seeks for the performance optimization only with variation of piston mass, 2^{nd} fill pressure in order to maximize the projectile speed.

For measuring the projectile speed, solenoids is installed along the driven part and neodymium magnet (2000 gauss) is inserted in the projectile as a counter part. From this configuration, we

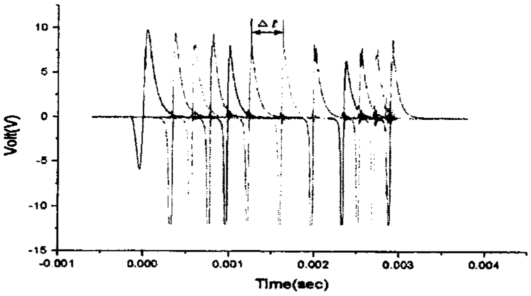


Fig. 6 Measurement of signals produced by moving projectile

could measure the induced electromotive force using an oscilloscope (Lecroy 9354A, 4ch). The projectile signal was measured relative to the trigger signal on the oscilloscope. The average speed between each solenoid can be calculated with the time lapse and the distance between the solenoids. Figure 6 shows signals measured from the projectile motion. Δt represents the time lapse for a projectile to dislocate a fixed distance.

There are many types of parameters that can be used in the optimization of facility performance according to its intrinsic characteristics. These are categorized into either geometry parameters or operation parameters. Geometry parameter may determine the physical configuration of the facility, while operation parameters are attributed to the operational condition and can be varied to meet test requirements. Table 1 summarizes details of two types of parameters.

It should be noted that geometry parameters can not be used as optimization variables in this study because their dimension should be fixed with the facility set up and can not be varied for optimization thereafter. A compressed air is used as propellant gas to accelerate piston in the tube. The pressure levels both in the driver and the driven and the piston mass are of crucial in determining the performance of the system. And these were selected as performance parameters for the optimization. Generally, 2^{nd} fill pressure should be determined in association with the pressure level in the first driver to obtain the performance enhancement. Also, the piston mass should be chosen to avoid any damage and permanent deformations of facilities. Table 2 shows the details of operating parameters and constraints in the study.

Table 3 shows performance parameters and their values used for performance optimization of hypervelocity launcher system.

Table 1 The parameters of the hypervelocity launcher

Comp. Parameters	1st Driver	2nd Driver	Chamber	Driven
Operating Parameters	Fill Pressure	Propellant Gas Piston Mass Fill Pressure	Diaphragm Rupture Pressure	Projectile Mass
Geometry Parameters	Length of the 1st Driver	Length of the 2nd Driver	Contr. Section Angle	Length of Driven

Table 2 Operating parameters and constraints used in this study

Operating Parameters	Side Constraint
2nd Fill Pressure(bar)	Maximum 1st Driver Pressure≦90bar Accurated handling to supply pressure (easy to operate)
Piston Mass (g)	l(piston length)/d(piston diameter)>2 The damage consideration due to a shock

Table 3 The parameters used in this study

Components	2nd Driver		Chamber
Parameters	Piston Mass (g)	Pump tube Fill Pressure (bar)	Steel Diaphragm Thickness (×1.0mm)
Variation	318, 714, 964	1, 2, 3	1.0

4. Response Surface Method and Genetic Algorithm for Launcher System Optimization

It is not difficult to obtain the optimized solution if the objective function can be expressed as a mathematical function although the optimization process requires a large number of analysis runs. The present study, however, not only deals with the non-mathematical objective function but also requires an additional examination in reducing the optimization cost and time by minimizing the test points. When conventional a Gradient Based Methods (GBM), that require the gradient information of design variables at each design point is implemented. The number of experiment points can be large. Therefore, it is better to use a statistically approximated design surface created by ANOVA (Analysis of Variance) and Regression Analysis. In this approach, a polynomial function is usually constructed to approximate the response surface of corresponding design variables.

The response surface method (RSM) (Jeon, 2000) is a statistical approach which utilizes the Design of Experiment (DOE) theory. It constructs multidimensional surface (response surface) using the experimental data, hence it is possible to predict the response of the non-experimented region. In most case the 2^{nd} order polynomial function of the design variables represents a satisfactory to the response surface.

$$y_{predict}=b_0+\sum_{i=1}^{k}b_i x_i+\sum_{i=1}^{k}b_{ii}x_{ii}^2+\sum_{i=1}^{k-1}\sum_{\substack{i=2\\ j\neq i}}^{k}b_{ij}x_i x_j \quad (6)$$

Here, $x_1, x_2, \ldots, x_k$ are the design variables, $b_i (i=1, 2, \ldots, k)$ are the coefficients of regression function, and $y_{predict}$ is a predicted value from regression function.

The adjusted R square (R_{adj}^2)[4], which is defined as Eqn. (7) is used for evaluating confidence of constructed response surface model.

$$R_{adj}^2=1-\frac{SSE/(n-p)}{SYY/(n-1)} \quad (7)$$

In Equ. 7 SSE is the error sum of squares, SYY the total sum of squares, n the number of experiment, and p the number of regression coefficients; (n-p) means the Design of Freedom (DOF) of SSE and (n-1) is DOF of SYY. As can be seen in the definition, R_{adj}^2 is a number how well it represents the real surface. It means the perfect representation to real surface if R_{adj}^2 is equal to unity. Typical values for R_{adj}^2 are $0.8 \leq R_{adj}^2 \leq 1.0$ when the observed response values are accurately predicted by the response surface model (Giunta, 1996).

With proper construction of the regression model the analysis runs or function calls are not a computational burden, therefore a global optimization algorithm is employed to obtain the optimum solution. GENOCOP III, one of the genetic algorithms developed by Z. Michalewicz (1996) has been implemented in this study. The

Fig. 7 Response surface construction procedure (Jeon, 2000)

code can handle not only the unconstrained optimization problems but also the constrained problems.

5. Formulation for Optimization

Two performance parameters are selected to investigate its influence on the performance such as projectile speed : the piston mass and the 2^{nd} driver fill pressure. Non-dimensional design variables are introduced using Eqn. (8).

$$x_i = \frac{X_i - (X_{max,i} + X_{min,i})/2}{(X_{max,i} - X_{min,i})/2}, \quad i = 1, \ldots, k \tag{8}$$

Here X_i are dimensional design variables, x_i are a non-dimensional variables. For the purpose of system optimization, the formulation is followed as

$$\textit{Maximize projectile velocity} \tag{9}$$

$$\text{Domain constraints: } 1\text{bar} \leq \text{fill pressure} \leq 3\text{bar} \tag{10}$$
$$318\text{g} \leq \text{piston mass} \leq 964\text{g}$$

Here, the projectile velocity is approximated by quadratic response surface using the experimental data and the first driver pressure is limited by 90 bar because of the safety of our facility.

6. Results and Discussion

Response surface approximates the real response by using a few well planned and selected experiment results. The accuracy of the response surface is, of course, dependent on the number of experiment results that can be used for constructing the surface. However, it is worth pointing out that the total number of experiment increases exponentially as more design variables are considered. Thus, it is necessary to properly restrict the total number of experiments to reduce total amount of money and time while having the surface with the reasonable accuracy. The 3^k full factorial method is one of methods to fulfill this primary requirement, which has three non-dimensional levels, -1, 0, 1. Total number of experiments would be 3^k. (k is a number of design variables) As expected, this is a good method to be applied to a system with a small number of design variable, such as the current problem. Thus, we can select 9 experiments points which is the minimum set of experiments required to construct the response surface. Table 4 shows the

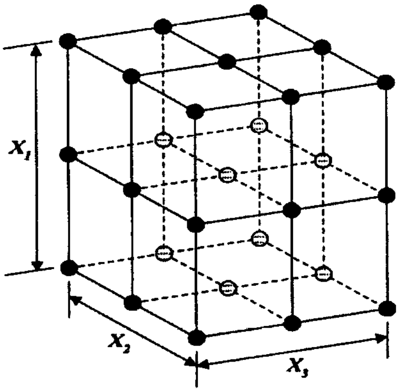


Fig. 8 3^k full factorial method

Table 4 Experimental results and parameters

	X_1 (Piston mass)	X_2 (1st driver pressure)	Y_1 (Vel., m/s)	Y_2 (Pres., bar)	Y_1 error	Y_2 error
1	964.00000 (+1)	1.00000 (−1)	698.00000	50.00000	3.86%	-2.73%
2	714.00000 (0.22)	1.00000 (−1)	698.00000	54.00000	-5.03%	-0.53%
3	318.00000 (−1)	1.00000 (−1)	612.00000	54.80000	1.33%	3.02%
4	964.00000 (+1)	2.00000 (0)	600.00000	80.30000	-4.51%	3.14%
5	714.00000 (0.22)	2.00000 (0)	769.00000	81.00000	3.45%	1.13%
6	318.00000 (−1)	2.00000 (0)	698.00000	74.50000	0.07%	-4.62%
7	964.00000 (+1)	3.00000 (+1)	612.00000	79.80000	0.02%	1.44%
8	714.00000 (0.22)	3.00000 (+1)	789.00000	82.00000	1.08%	-0.77%
9	318.00000 (−1)	3.00000 (+1)	811.00000	81.30000	-1.07%	2.19%

response value at these points.

Figure 9(a) shows the response surface of projectile velocity and figure 9(b) depicts response surface plot of first fill pressure. The regression models of the projectile velocity and the fill pressure are as follows.

$$F(\vec{x}) = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_2 + b_4 + x_1^2 + b_5x_2^2$$

Regression coefficients for each case are given at Table 5 and 6.

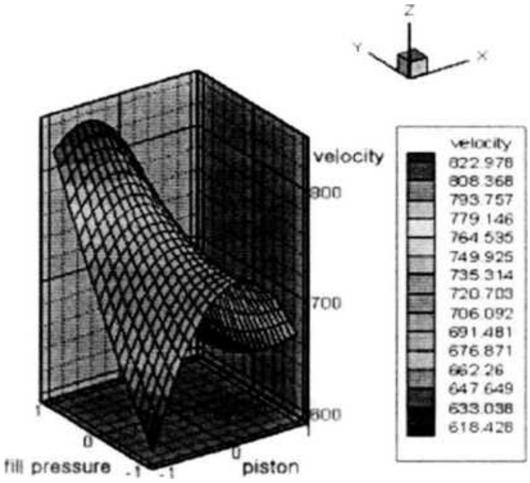


Fig. 9(a) Constructed regression model for projectile velocity

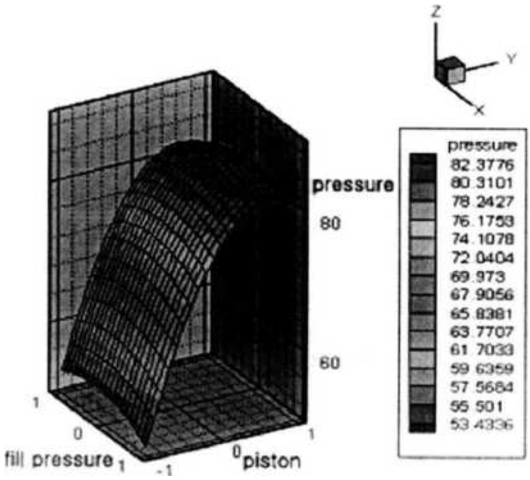


Fig. 9(b) Constructed regression model for fill pressureb

Table 5 Regression coefficient of the projectile velocity

Regression	Coefficient
b0	742.444
b1	-34.000
b2	-35.167
b3	14.333
b4	-80.167
b5	71.250

Table 6 Regression coefficient of the fill pressure

Regression	Coefficient
b0	80.0778
b1	-14.0500
b2	-0.0833
b3	-11.6167
b4	-2.2167
b5	-0.0825

Table 7 The optimum operating condition from a GA

x_1	x_2	X_1	X_2	*Velocity* (*m/s*)	*Pressure* (*bar*)
-0.559445381	1	460.2991419	3	837.73	81.44

x_1 : Coded variables, X_1 : Natural variables

To assess the accuracy of approximate surface, R_{adj}^2 is evaluated both at velocity surface and at pressure surface and the calculated values are 0.8088 and 0.9488 respectively. These values repre sent a very good accuracy within 5% error as can be seen at table 4. The constructed regression models are used with GA optimization algorithm (GENOCOP III) and yielded an optimization result after 750 generations (Lee, 2002). Table 5 shows optimal conditions of the piston mass, and the first driver pressure (Choi, 2002).

The optimum solution obtained by GA algorithm are verified by performing the experiment. The experiments shows the projectile speed of 835m/s which shows a good agreement with a predicted GA less than 0.3% error. This confirms that two stage gun should be operated with an piston mass of 460g and 3 bar fill pressure condition. Also the optimization can improve the performance of the facility by gaining more projectile speed of 24m/s compared to the previous maximum projectile speed. Moreover about 20% of velocity improvement from the velocity of baseline launcher system (698m/s) can be attained through the optimization.

7. Summary and Conclusions

In this study the method of finding optimal operational conditions of hypervelocity launcher is presented. The response surface is constructed based on experimental results. The GA is used to find the operational conditions for the constructed maximum projectile speed. The optimization results are confirmed by the experimental test with a good accuracy. Thus, two stage gas gun is better to be operated with a piston mass of 460g in the higher driver diver pressure condition. Also the optimization can improve the performance of the facility by gaining more projectile speed of 24m/s compared to the previous maximum projectile speed.

In addition, this study may show the possibility that the optimization process ca be done using the minimum number of experiment results without resorting to expert's experiences. Also, this approach may be applied to similar problems having an explicit functional relationship of objective function over the design variables. From this study, 20% velocity improvement of the Konkuk university hypervelocity launcher system has been attained.

Acknowledgments

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