Multi-Response Optimization of Input Parameters of Two Stage Light Gas Gun for Improved Performance

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***Abstract*—Two stage light gas gun (2SLGG) is the most appropriate technique to simulate the orbital debris impact on the space aircraft. There are number of parameters that affect the performance of 2SLGG, but for the present study; the factors under consideration are 'Powder mass' (PM), 'Charge pressure of light gas' (CP) and 'Projectile mass' (PJM). In order to find the levels of different input parameters, the various trial simulations are run by varying the input parameters values in specific range. The three input parameters are taken at three levels i.e. PM at 2000, 2200 and 2400 grams, CP at 10, 12 and 14 bar and PJM at 15, 25 and 35 grams. The optimum combination of levels of input parameters is determined using Grey relational analysis (GRA) technique in order to maximise the 'Muzzle velocity' (MV) and to reduce the 'Maximum pressure in high pressure section' (MPHPS). As the cost of performing experiments in 2SLGG is very high, all the trials are performed in CESAR simulation software. It is concluded that the 2SLGG produces highest MV with reduce MPHPS, when the PM is 2000 gram, CP is 14 bar and PJM is 15 gram.**

Keywords*— *Two stage light gas gun, Muzzle velocity, Powder mass, Projectile mass, Grey relational analysis.

I. Introduction

A two-stage light-gas gun (2SLGG) is one of the most beneficial tools for the acceleration of projectile in order to simulate the space debris impact on the spacecraft [1]. A 2SLGG is used under extremely severe launch conditions in order to obtain higher projectile velocity. Thus, much effort and special care are necessary to prevent the gun components from being damaged and to accelerate a fragile projectile [2]. A great deal of research in the projectile acceleration could be done by producing the high-energy working gas efficiently and by reducing the maximum projectile base pressure [3]. However, the principal and the basic structure of a 2SLGG have been unchanged so far.

In order to maximize the final muzzle velocity and minimise the damage of various gun components, the selection of various input parameters is very critical. There are various input parameters for 2SLGG like powder mass, light gas charge pressure, piston mass, projectile mass, petal valve burst pressure, level of vacuum in launch tube, piston coefficient of friction with walls of pump tube, etc. [3,4,5]. But for the present study, input factors which significantly affect the performance of 2SLGG are selected as 'Powder mass' (PM), 'Charge Pressure of light gas' (CP) and 'Projectile mass' (PJM) [6,7]. The motivation for the present study is to determine the optimum combination of these input parameters in order to maximise the 'Muzzle velocity' (MV) and to minimise the 'Maximum pressure in high pressure section' (MPHPS).

There are various multi-response optimization techniques like Taguchi methods, Response surface methodology, Grey relational analysis, Multi-criteria decision making etc. The technique utilized for present study is Grey relation analysis (GRA) because it can analyse complex relationships between multiple responses, especially when dealing with limited data. It can also be used in conjunction with Taguchi methods or other optimization techniques [8]. The rest of the paper is organized as follow: Section 2 describes the methodology adopted for the present study. Section 3 gives brief about 2SLGG and its working. How the various different input parameters and their levels are identified, is explained in Section 4. Section 5 explains the technique used to find optimum combination of levels of input parameters. Finally, practical implications and conclusions are given in Section 6 and 7 respectively.

II. Methodology

The present study determines the optimized parameters and their levels for the improved performance of 2SLGG. From the literature survey, it is observed that PM, CP and PJM are the parameters, which significantly affect the projectile MV and MPHPS. In order to investigate the levels of input parameters, the simulation trials are run for different input parameter value using the CESAR simulation software for 29 mm launch tube diameter. The PM is varied from 1400 gram to 3400 gram in the step of 200 gram. Similarly, the CP and PJM are varied from 4 to 22 bar (step of 2 bar) and 15 gram to 60 gram (step of 5 gram) respectively and corresponding results are observed for MV and MPHPS. When one input parameter is varying in the specific predefined range, the others are kept at constant level. The constant level of PM, CP and PJM are 2200 gram, 14 bar and 15 gram. It is well known that the cost of performing experiments in 2SLGG is very high. So, in order to consider the cost and time factors, all the trials are performed in CESAR simulation software. In the end, GRA technique is utilized to find the optimum combination of parameter for the improved performance.

III. TWO STAGE LIGHT GAS GUN (2SLGG)

A 2SLGG consists of powder chamber, pump tube, launch tube and high pressure section (HPS). The consumable items include piston, light gas, petal valve and projectile assembly along with sabot. The schematic of 2SLGG is given in Figure 1. The powder chamber contains the propellant in specified amount and piston is placed on the rear side of pump tube and adjacent to powder chamber. Pump tube is filled with light gas i.e. helium, hydrogen or nitrogen at appropriate pressure. The HPS is a coupling between pump tube and launch tube and it contains petal valve, which is designed to burst at predefined pressure. The projectile and sabot assembly is placed in launch tube and adjacent to HPS. It is necessary to maintain vacuum in launch tube in order to provide minimum resistance to the projectile assembly.

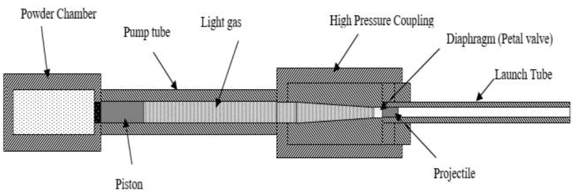

Figure 1: Schematic of 2SLGG [9]

As the propellant burns, it allows the piston to move and compress the light gas to high pressure in pump tube. When the pressure in pump tube reaches at predetermined level, petal valve burst inside HPS. This allows the projectile assembly to move and accelerate inside the launch tube.

IV. SELECTION OF INPUT PARAMETERS AND THEIR LEVELS

As mentioned earlier, there are various input parameters which affect the performance of 2SLGG. From the literature survey, it is found that the factors which significantly affect the performance and results of 2SLGG are PM, CP and PJM [6, 7]. PM is the amount of propellant that is to be filled in powder chamber. CP is the light gas pressure in the pump tube and finally PJM is the mass of projectile along with sabot.

For the selection of levels of various input parameters, the trial simulation has been run using CESAR simulation software. The validation of CESAR simulation model has been done with experimental data. It is found that average error between experimental and simulation data is 8% only and that is quite acceptable. The PM is varied from 1400 gram to 3400 gram in the step of 200 gram and corresponding results are observed for MV and MPHPS. Similarly, the CP of light gas and PJM are kept in the range of 4 bar to 22 bar (Step of 2 bar) and 15 gram to 60 gram (Step of 5 gram) respectively. When one input parameter is varying in the specified range, the others are kept at constant level. The constant level for PM, CP and PJM are 2200 gram, 14 bar and 15 gram. The various graphs for these trials simulations are given in Figure 2. It is to be noted that in Figure 2, units of MV, MPHPS, PM, CP and PJM are m/s, bar, gram, bar and gram respectively.

Figure 2(a) and 2(b) shows the effect of change in PM on output parameters. It is clear from Figure 2(a) that PM and MV are directly proportional to each other. Similarly, the MPHPS also increases with increase in PM. The reason is obvious and clear. As, the amount of propellant increases, the pressure behind the piston also increases, which results in rise in maximum pressure in HPS with increase in muzzle velocity. In general practice, the maximum pressure in HPS should not rise above 6000 bar. That's why the level of powder mass is taken as 2000 gram, 2200 gram and 2400 gram.

Figure 2(c) and 2(d) shows the effect of change in CP on MV and MPHPS. It is investigated from Figure 2(c) that with increase in CP up to certain limit, MV also increases, and after that it starts decreasing. Similar is the case with MPHPS (Figure 2(d)). Let us assume the case when there is no light gas inside the pump tube. In that case, there is no restriction to the movement of piston and it can move with higher velocity. As we fill the pump tube initially at low pressure, then there is less hurdle to movement of piston. But, as the charge pressure increases to certain limit, it start posing significant hurdle to motion of piston. The velocity of piston decides the base pressure behind the projectile as well as final muzzle velocity. As the light gas is filled with low charge pressure like 4 to 8 bar, there will be less hindrance in the motion of piston. Thus piston can move with high velocity, which will increase the MPHPS and MV. After certain limit of charge pressure like 8 bars, increase in charge pressure poses hurdles for the motion of piston. As a result, there is reduction in MPHPS and also in MV. So, it is clear that at low charge pressure, MV is high but MPHPS is also significantly high. For this reason, level of charge pressure is taken as 10 bar, 12 bar and 14 bar.

Figure 2(e) to 2(f) shows the effect of variation in PJM on response parameters. It is clear from Figure 2(e) that with increase in PJM, MV decreases. It is very much clear that the pressure behind the projectile base is same and only projectile mass is varying. Thus, momentum is same for projectile as earlier i.e. increase in mass leads to decrease in muzzle velocity and vice versa. As the HPS is located behind the projectile, so change in mass of projectile do not have any significant impact on maximum pressure in HPS. It is clear from Figure 2(f) that maximum pressure is 4067 bar and minimum pressure is 3972 bar. So, the range is only 95 bar with mean of around 4019 bar. For this reason, level of projectile mass is taken as 15 gram, 25 gram and 35 gram.
25 gram and 35 gram.

V. GRA TECHNIQUE

Grey relation analysis (GRA) technique was originated by Julong Deng, professor at Huazhong University of Science and Technology, Wujan, China in 1982 [10]. Generally, the black is represented as lack of information and white shows full of information. So, the information that is either incomplete or undetermined is called grey. Thus, the system having incomplete information is called Grey system [11]. GRA is a technique used to determine the optimum conditions of various input parameters to obtain the best quality characteristics [12]. It is broadly applied in evaluating or judging the performance of a complex project with meagre information. It can also be used to derive optimum conditions for multi-objective problems by providing weightages to individual responses [13]. For the present study, the selected levels of various input parameters are given in Table I.

TABLE I. VARIOUS INPUT PARAMETER WITH THEIR LEVEL

Sr. No.	Parameter/ Level	Level 1	Level 2	Level 3
1	Powder Mass (PM) in gram	2000	2200	2400
2	Charge Pressure (CM) in bar	10	12	14

3	Projectile Mass (PJM) in gram	15	25	35

As the numbers of factors are three and level of each factor is also three, the total numbers of experiments performed with all the possible combination are 27. The arrangement of various experiments is given in Table II.

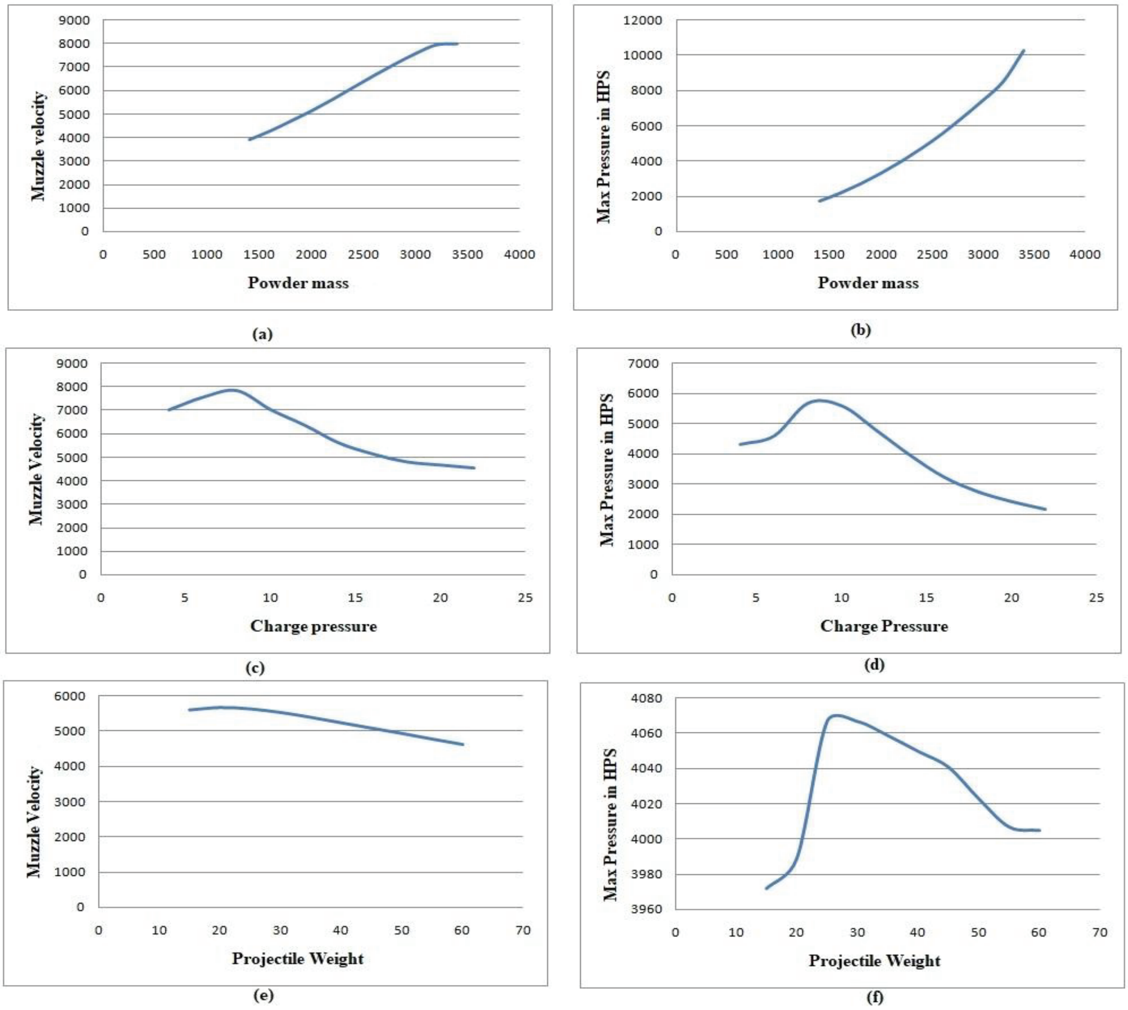

Figure 2: Effect of various input parameters on muzzle velocity and maximum pressure in HPS

TABLE II. DESIGN OF EXPERIMENTS

Sr. No.	PM	CP	PJM
1	2000	10	15
2	2000	10	25
3	2000	10	35
4	2000	12	15
5	2000	12	25
6	2000	12	35
7	2000	14	15
8	2000	14	25
9	2000	14	35
10	2200	10	15
11	2200	10	25
12	2200	10	35
13	2200	12	15
14	2200	12	25
15	2200	12	35
16	2200	14	15
17	2200	14	25
18	2200	14	35
19	2400	10	15
20	2400	10	25
21	2400	10	35
22	2400	12	15
23	2400	12	25
24	2400	12	35
25	2400	14	15
26	2400	14	25
27	2400	14	35

The output parameters for each experiment are MV and MPHPS. It is well known that the cost of performing experiments in two stage light gas gun is very high. So, in order to consider the cost and time factors, all the trials are performed in CESAR simulation software. The output values for each experiment are given in Table III. The output values after normalizing is also given in Table III. For MV, 'Higher the better' formula is preferred (Equation 1) and for MPHPS, formula utilized for normalizing is 'Smaller the better' (Equation 2) [14].

$$X_i^*(k) = \frac{X_i^0(k) - \min X_i^0(k)}{\max X_i^0(k) - \min X_i^0(k)} \qquad \text{Equation (1)}$$

$$X_i^*(k) = \frac{\max X_i^0(k) - X_i^0(k)}{\max X_i^0(k) - \min X_i^0(k)} \qquad \text{Equation (2)}$$

Where $X_i^0(k)$ is original sequence, $X_i^*(k)$ is the sequence after data pre-processing, $max\ X_i^0(k)$ is the largest value of $X_i^0(k)$ and $min\ X_i^0(k)$ is the smallest value of $X_i^0(k)$.

TABLE III. OBSERVED OUTPUT VALUES AND NORMALIZED VALUES

Sr. No.	Output		Normalizing	
	MV (m/s)	MPHPS (bar)	MV (m/s)	MPHPS (bar)
1	6587	4785	0.645	0.589
2	6184	4979	0.476	0.535
3	5695	4982	0.27	0.534
4	5804	4054	0.316	0.791
5	5789	4159	0.31	0.762
6	5455	4135	0.169	0.769
7	5134	3299	0.034	1
8	5219	3365	0.07	0.982
9	5052	3359	0	0.983
10	7033	5600	0.833	0.363
11	6500	5856	0.609	0.292
12	5961	5906	0.382	0.278
13	6373	4803	0.555	0.584
14	6180	4964	0.474	0.539
15	5769	4952	0.301	0.542
16	5617	3972	0.237	0.814
17	5647	4067	0.25	0.787
18	5402	4059	0.147	0.79
19	7431	6512	1	0.11
20	6803	6866	0.736	0.012
21	6230	6911	0.495	0
22	6889	5634	0.772	0.354
23	6537	5859	0.624	0.291
24	6063	5875	0.425	0.287
25	6129	4717	0.453	0.607
26	6054	4851	0.421	0.57
27	5734	4841	0.287	0.573

After normalizing the response parameters, the deviation sequence (Δ_{0i}) and grey relational coefficient (GRC) is calculated using Equation 3 and 4 respectively [14].

$$\Delta_{0i} = X_0^*(k) - X_i^*(k) \qquad \text{Equation (3)}$$

$$GRC = \frac{\Delta_{0\,min} + \rho\,\Delta_{0\,max}}{\Delta_{0i} + \rho\,\Delta_{0\,max}} \qquad \text{Equation (4)}$$

Where Δ_{0i} is difference between the corresponding values in the reference and feature sequence. $\Delta_{0i\,min}$ is the minimum of Δ_{0i} values and $\Delta_{0i\,max}$ is the maximum of Δ_{0i} values. ρ is the distinguishing coefficient and its values varies from 0 to 1. Generally its values is taken as 0.5. Finally grey relational grade is calculated as average of grey relational coefficient for MV and MPHPS in order to convert two responses into single values and is given in Table IV.

TABLE IV. DEVIATION SEQUENCE, GREY RELATIONAL COEFFICIENT AND GREY RELATIONAL GRADE

Deviation Sequence		Grey relational coefficient		Grey Relational grade
MV (m/s)	MPHPS (bar)	MV (m/s)	MPHPS (bar)	
0.354	0.411	0.584	0.548	0.566
0.524	0.465	0.488	0.518	0.503
0.729	0.465	0.406	0.517	0.462
0.683	0.209	0.422	0.705	0.563
0.690	0.238	0.420	0.677	0.548
0.830	0.231	0.375	0.683	0.529
0.965	0	0.341	1	0.670
0.929	0.018	0.349	0.964	0.657
1	0.016	0.333	0.967	0.650
0.167	0.637	0.749	0.439	0.594
0.391	0.707	0.560	0.413	0.487
0.617	0.721	0.447	0.409	0.428
0.444	0.416	0.529	0.545	0.537
0.525	0.460	0.487	0.520	0.503
0.698	0.457	0.417	0.522	0.469
0.762	0.186	0.396	0.728	0.562
0.749	0.212	0.400	0.701	0.550
0.852	0.210	0.369	0.703	0.536
0	0.889	1	0.359	0.679
0.263	0.987	0.654	0.336	0.495
0.504	1	0.497	0.333	0.415
0.227	0.646	0.686	0.436	0.561
0.375	0.708	0.570	0.413	0.492
0.575	0.713	0.465	0.412	0.438
0.547	0.392	0.477	0.560	0.518
0.578	0.429	0.463	0.537	0.500
0.713	0.426	0.412	0.539	0.475

Finally, the main effect for grey relational grade is calculated by averaging the corresponding levels values for particular parameter and results are shown in Table V. The optimised value for each parameter is maximum among three levels. It is observed that the optimised parameter for 2SLGG for obtaining highest MV with reduced MPHPS are level 1 of PM (2000 gram), level 3 of CP (14 bar) and level 1 of PJM (15 gram).

TABLE V. MAIN EFFECTS OF GRAY RELATIONAL GRADE

	PM	CP	PJM
Level 1	0.572	0.514	0.583
Level 2	0.518	0.516	0.526
Level 3	0.508	0.569	0.489

VI. PRACTICAL IMPLICATIONS

As stated earlier, the ultimate aim of the 2SLGG is to simulate the orbital debris impact on space aircraft. At the same time, it is very much essential to maintain the integrity of the light gas gun. This paper provides insights for scientists and decision makers working in the hypervelocity region by providing optimum combination of input parameter for 2SLGG in order to achieve highest possible muzzle velocity with minimum peak pressure in high pressure section. It is obvious that 2SLGG operates under extreme severe launch condition; the optimum combination of input parameters prevents the gun components from being damaged and ensures long life of gun.

VII. Conclusions

The present paper provides selection of input parameters and their levels for 2SLGG in order to achieve highest MV and minimum MPHPS. There are number of factors that affect the performance of 2SLGG, but for the present study; the factors under consideration PM, CP and PJM. The GRA technique is used to find optimum combination of input parameters that gives the desired output. It is conclude that the 2SLGG produce highest possible MV with reduce MPHPS, when the PM is 2000 gram, CP is 14 bar and PJM is 15 gram. There are some limitations associated with this study. All the simulations are performed for 29 mm calibre launch tube. So the results can be different for other calibre gun. In the future, optimization of input parameters can be done for different calibre guns. At least three physical experiment must be done in the nearby future with investigated level of input parameters in order to validate whether they provides the desired results or not.

Conflicts of Interests

The authors declare that there are no conflicts of interest in this study

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