Functional Reliability Prediction of Pyrotechnic Separation Device using Response Surface Model

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ABSTRACT

Pyrotechnic separation device is used in military and aerospace application because of many benefits such as fast operating time, simple structure, and light weight. The reliability the pyrotechnic device is very important due to its one-shot nature. Thus, reliability prediction of the device should be considered from the beginning stage of its design.

This paper introduces an approach to predict functional reliability of pyrotechnic separation device. The overall procedure consists of the following steps: 1) design parameters affecting the pyrotechnic separation device are identified, 2) design of experiment is defined through the sensitivity analysis about parameters, 3) response surface model is constructed using polynomial equation. 4) The functional reliability is calculated using Monte Carlo simulation by iterating response surface model.

1. INTRODUCTION

PMD (Pyrotechnic Mechanical Device), which is widely used in aerospace and military systems, has been used in separation and ignition devices due to its lightness, fast operation time and simplicity of structures. However, since PMD is a one-shot device, it cannot be reused and repaired if a failure occurs. Therefore, predicting the reliability of PMD is the most essential factor.

Previously, it was difficult to calculate the reliability through computational analysis. So, some people tried to calculate the failure probability through experiments. However, in order to demonstrate a reliability of 0.99 at a 90% confidence interval, at least 240 tests should be succeeded without a fail. That means the demonstrate reliability needs some expenses.

In this study, the reliability prediction of the separation device is introduced. Performance modeling is used to predict the reliability of separation device and the response surface method is applied to simplify complicated modeling.

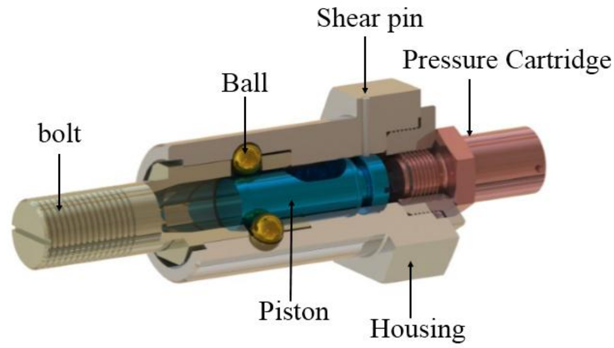


Figure 1. Configuration of pyrotechnic separation device

2. OVERALL OF PYROTECHNIC SEPARATION DEVICE

Prior to predicting reliability, we first introduce the target separation device. The separation device to be used in this study is a 1/2’’ ball type and a schematic diagram is shown in figure 1. Here, 1/2’’ means the size of the bolt.

This device is mainly used that restrains a rocket or a missile to a launching platform and releases a restraint when a signal is applied so that it can be fired.

The device consists of bolt, piston, shear pin, housing, restraining balls, and pressure cartridges. Here, PC-800 was used as the pressure cartridge. Upon the firing current the pressure cartridge generates combustion gas that pushes out the piston to bolt. When the piston breaks the shear pin and comes into contact with the bolt, the restraining ball moves into the piston and the restraint is released. Finally, piston hit the bolt and throw away the bolt.

3. LUMPED PARAMETER MODELING OF SEPARATION DEVICE

Among those components, the pressure generated in the pyrotechnic pressure cartridge is the most important parameter in terms of performance modeling and reliability prediction. Therefore, mathematical modeling is performed

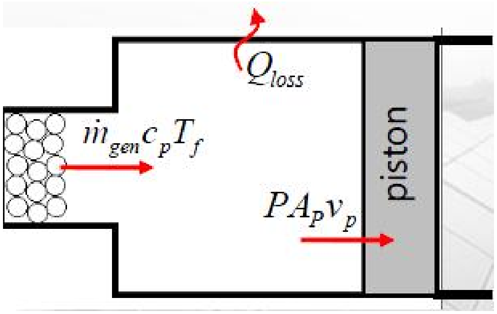


Figure 2. Modeling of pressure cartridge

to calculate the pressure generated in the pressure cartridge. To this end, the pressure cartridge section is simplified as shown in figure 2.

As shown in figure 2, the mass conservation and the energy conservation equation are applied to the simplified pressure cartridge to calculate the pressure generated by the combustion of explosives. See the reference for detail.

$$\frac{d(\rho V)}{dt} = \dot{m}_{gen}$$

$$\dot{\rho} = \frac{\dot{m}_{gen} - \rho(A_b r_b + A_p v_p)}{V} \tag{1}$$

$$\frac{d(\rho V c_p T)}{dt} = \eta_p(\dot{m}_{gen} c_p T_f) - PA_p v_p - \dot{Q}_{loss}$$

$$\dot{P} = \frac{\eta_p \dot{m}_{gen} R\gamma T_f - (\gamma - 1)(PA_p v_p + \dot{Q}_{loss}) - P\dot{V}}{V} \tag{2}$$

After the performance modeling, the probability distribution is applied to each input parameters. Probabilistic values of input parameter are based on experimental data and reference documents. If not, it is assumed to be normal distribution.

4. DEFINE A LIMIT STATE FUNCTION

We employ a stress-strength model to figure out the functional reliability. The stress is the force acting on the piston by the pressure from pressure cartridge. The strength covers the shear force cutting the shear pin, friction force of the O-ring and the restraint ball. Since the above values change with time, energy can be calculated from the performance model.

$$E_{stress} = F_{pressure} \tag{3}$$

$$E_{resistance} = F_{shear} + F_{oring} + F_{ball} \tag{4}$$

The eq. (3), (4) are used to define the limit state function of the separation device such as eq. (5).

$$\mathrm{R} = \mathrm{g}(E_{stress} - E_{resistance}) \tag{5}$$

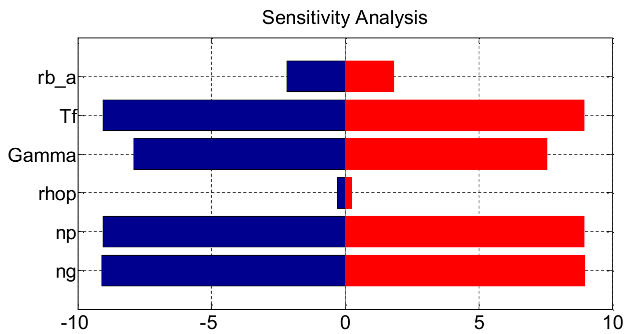
5. SENSITIVITY ANALYSIS

To calculate the reliability through Eq. (5), the values of Eqs. (3) and (4) should be calculated through Eqs. (1), (2). However, computation is time consuming and costly because of the complexity of the equation and many variables to calculate for reliability. In order to save the calculation time the performance model should be simplified by response surface method. And we have to select the dominant variables which affects the performance by applying the sensitivity analysis to construct the appropriate response surface. For each variable, change the value of ±10% and observe the change of the result value. Here, we present the result of applying the sensitivity analysis to the input variables used to calculate the combustion pressure generated by explosives.

Figure 3 shows the sensitivity analysis of input variables about combustion pressure. The red graph shows a change in pressure when the pressure is changed by +10% and the green graph shows a pressure change by -10%. Figure 3 shows that the sensitivity of 6 variables [A_b (burning area), ZPP (mass of ZPP), T_f (flame temperature), gamma, η_p (efficiency of combustion), ng (gas ratio)] is more than 5%. However, gamma and η_p are a constant that cannot have a physically probability distribution. So, the response surface is constructed by using 4 parameters except gamma, η_p.

6. RESPONSE SURFACE MODEL

These 6 variables are used to simplify the performance modeling by applying the response surface method. When constructing the response surface, sample of +2.5 σ, +3σ, +4.5σ are extracted and used for each input variable. The standard deviation of each input variable is assumed to be 5% of the mean value.



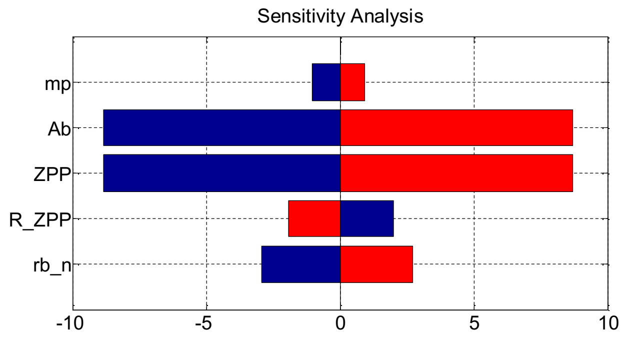


Figure 3. Sensitivity Analysis

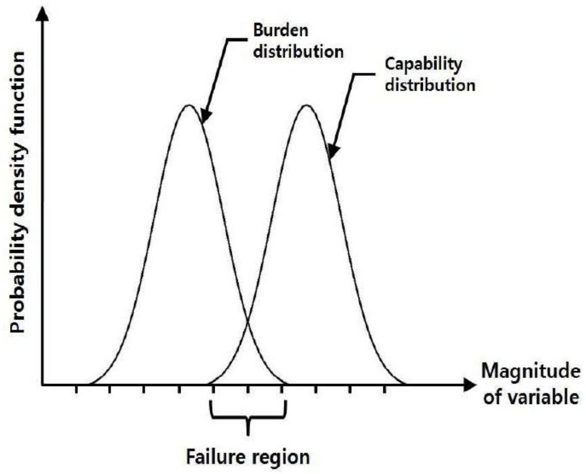


Figure 4 Burden-Capability Model

The response surface is approximated by a 2nd order polynomial equation. At this time, the coefficient of determination R2 is 0.9758, which shows that a fairly accurate response surface is produced.

7. FUNCTIONAL RELIABILITY OF SEPARATION DEVICE

After the response surface is constructed, it is applied to the limit state function to calculate the reliability. The reliability is calculated by applying the Burden-Capability model as shown in figure 4.

The reliability is calculated using Monte-Carlo simulation through 1,000,000 iteration.

As a result of the reliability prediction, the reliability of the separation device is calculated as 0.9983 and the deviation using Monte-Carlo simulation is 0.024.

8. CONCLUSION

In this study, the reliability of the separation device used in aerospace industry was predicted. For this purpose, combustion and performance modeling was generated, and the limit state function for the separation phenomena was defined. To solve the complicated performance model, the response surface using the 2nd order polynomial equation was applied. Finally, the reliability of the separation device was predicted by Monte-Carlo simulation with 1,000,000 iterations.

Table 1. Result of reliability prediction.

Reliability	COV (δ)
0.9983	0.024

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