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Reliability Evaluation of a Pin Puller via Monte Carlo Simulation

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Abstract

A Monte Carlo (MC) simulation was conducted to predict the reliability of a newly developed pyrotechnic pin puller. The reliability model is based on the stress–strength interference model that states that failure occurs if the stress exceeds the strength. In this study, the stress is considered to be the energy consumed by movement of a pin shaft, and the strength is considered to be the energy generated by pyrotechnic combustion for driving the pin shaft. Failure of the pin puller can thus be defined as the consumed energy being greater than the generated energy. These energies were calculated using a performance model formulated in the previous study of the present authors. The MC method was used to synthesize the probability densities of the two energies and evaluate the reliability of the pin puller. From a probabilistic perspective, the calculated reliability was compared to a deterministic safety factor. A sensitivity analysis was also conducted to determine which design parameters most affect the reliability.

Key words: Pin Puller, One-Shot, Reliability, Stress-Strength Model, Monte Carlo Simulation

Symbols and Abbreviations

A	Burning rate constant
$A1, A2$	Fitting coefficients for locking mechanism
A_b	Burning surface area (m^2)
A_p	Effective pin shaft area (m^2)
B	Stress
C	Strength
D	Failure (= C-B)
d_i	Pin inner diameter (m)
d_l	Start point of locking (m)
d_o	Pin outer diameter (m)
d_r	Release point of missile (m)
E	Energy (joule)
e	Burning distance of pyrotechnic charge column (m)
F	Force (kg m/s^2)
F_{lm}	Locking mechanism force (kg m/s^2)
F_{sh}	Shear force (kg m/s^2)
f	Function
g	Gravitational acceleration (9.8 m/s^2)
I	Indication function
l	Pin shaft displacement (m)
m_p	Pin weight (kg)
m_{pc}	Pyrotechnic charge amount (kg)
$\dot{m}_{gen}$	Mass generation rate (kg/s)
N	Number of iteration
n	Burning rate exponent
P	Chamber pressure (Pa)
Pr	Probability
Q	Unreliability
$\dot{Q}_{loss}$	Heat transfer rate (J/s)
R	Reliability
$\hat{R}$	Reliability from hit-or-miss method
R_g	Universal gas constant (8.3143×10^3 J/kilomole K)
r_b	Burning rate (m/s)
S	Full stroke (m)
s_D	Standard deviation
$T1, T2$	Fitting coefficients for locking mechanism
T_f	Gas flame temperature (K)
t	Time (s)
V	Volume (m^3)
V_i	Initial volume (m^3)

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v_p	Pin shaft velocity (m/s)
W_p	Work done by pin shaft (N)
Y0	Fitting coefficient for locking mechanism
Z	Normalized variable
Z_0	Lower limit of normalized variable

Greek Symbols

δ	Tolerance
γ	Ratio of specific heats
θ	Angle (Rad)
η_p	Correction factor
μ_{lp}	Load to pin friction coefficient
ρ	Density (kg/m^3)
ρ_p	Pyrotechnic charge density (kg/m^3)
σ	Standard deviation
Φ	Cumulative distribution function
$\mathit{\Phi}$	Probability distribution function

Subscripts

Con	consumed
Gen	generated
ld	load
lm	locking mechanism
or	O-ring
pc	pyrotechnic charge
pr	pressure
sh	shear

1. Introduction

In aerospace and military applications, pin pullers are used to release certain objects as part of activities such as stage separation, wing deployment, and jettisoning of payload fairings [1]. The pin shaft of the pin puller holds an object to be released, and the retraction of the pin shaft to a predetermined position results in release of the object. Figure 1 is a schematic of a newly developed pin puller. Typically, pin pullers are activated by combustion of pyrotechnics. The combustion gases generate the force necessary to drive the pin shaft to the predetermined position. Because the combustion of pyrotechnic substances is an irreversible process, a pin puller cannot be used any further once fired. In this context, it is usually called a "one-shot" device.

Because of their mission-critical functions, very high reliability is generally required for pin pullers. The "one-shot" attribute, however, makes it difficult to evaluate the reliability of the device. Because repeated tests to assess the function of the device are impossible, the reliability can only be evaluated by sampling some of the devices and fully testing them. Hence, a large number of the devices are needed to estimate the reliability, particularly with statistical significance. For example, approximately 3000 identical devices need to be tested, without a failure, to achieve 99.9% reliability at the 95% confidence level, which is the level usually required in aerospace and military applications. However, it would not be realistic to conduct tests with such a large number of samples because of the time and cost involved. In practice, there is no way to guarantee that the device will work successfully prior to actual use. This is why the reliability evaluation of one-shot devices is a troublesome issue. What is of practical importance is knowing what the reliability value is.

New approaches that do not depend upon a large number of firing tests are required to allow designers and manufacturers to have confidence in the successful operation of pin pullers. In the context of reliability being the probability of whether a device performs its function properly, performance modeling could be a good starting point. Considerable research on performance modeling of pyrotechnically actuated devices has been conducted in the last two decades [2-9]. This research has provided insights into the performance of such devices. Understanding devices' physics thoroughly through performance modeling makes it possible to assess functional margins and identify the failure mechanisms of devices. Of course, this type of information can rarely be obtained even from firing tests. However, most previous studies in this area have been focused on evaluating performance in terms of chamber pressure evolution versus time, for instance. Fairly little research has been conducted on approaches to combining calculation results with a reliability or functional margin. Bement and his coworker [10, 11] addressed reliability in relation to the performance variables obtained from small-sample tests. This approach, however, is based on a deterministic functional margin determined by dividing the delivered energy by the required energy. This approach does not provide probabilistic information on whether an item will function successfully, nor does it provide information on which design parameters should be carefully controlled to achieve high reliability. The present study was prompted by a lack of any previous work bridging performance modeling with reliability evaluation for pyrotechnically actuated devices. The purpose of this study was to develop a probabilistic method for evaluation of the reliability of a pin puller using performance calculation results, without expensive collection of firing data.

To evaluate the reliability of a newly developed pin puller, we employed a probabilistic design method based on the stress–strength interference model [12-14]. The model relies on the concept of failure occurring if the stress exceeds the strength. In the present study, the stress was considered to be the energy consumed by movement of the pin shaft, and the strength was considered to be the energy generated by combustion of pyrotechnic materials. Both the stress and the strength were easily determined from calculations made using the performance model proposed by the present authors previously [15].

The stress–strength interference model treats the stress and the strength as random variables, rather than point values, with probability distributions. The probability distributions of the stress and strength can be obtained by the Monte Carlo (MC) method, which takes into account the statistical characteristics of the design parameters involved in the performance model. Once these two distributions are obtained, failure can be defined in terms of the overlap between the two distributions. Using this scheme, we can solve the challenging problems of predicting how reliable the pin puller is and knowing which design parameters most affect its reliability.

2. Performance Modeling of the Pin Puller

This section summarizes the performance model formulation and validation of the pin puller, the results of which were used to develop the probabilistic stress–strength model described in the next section.

2.1 Pin puller basics

As Fig. 1 shows, the newly designed pin puller considered in this study consists of an initiator, a pin shaft, a housing, and a locking mechanism. The initiator, which is usually mounted on the housing using thread, contains a pyrotechnic charge and bridge wires. A shear pin is used to hold the pin shaft in place initially, and O-rings fitted on the pin shaft are used to prevent gases from leaking. As a firing current is applied to the bridge wires, the burning of a pyrotechnic charge pressurizes the expansion chamber of the housing. Highly pressurized gases exert a force on the pin shaft, resulting in the shear pin being cut off and accelerating the pin shaft toward the bottom of the housing. If the force generated is sufficient to overcome the forces resisting the movement of the pin shaft, the pin can be retracted to the predetermined position. This retraction results in a release (for our purposes, a missile release).

A particular energy absorption system, referred to hereinafter as a "locking mechanism," was devised to prevent the pin shaft from bouncing after reaching the end of the stroke. Locking is achieved by plastic deformation caused by dimensional interference between the stud of the housing and the bore of the shaft; that is, the diameter of the stud is slightly larger than that of the bore (see Fig. 1 for details). As the moving distance of the pin shaft increases, the pin shaft is eventually anchored because of energy dissipation by plastic deformation. In this respect, the locking mechanism is a special energy-absorbing system that converts the kinetic energy of the moving pin shaft into plastic deformation energy.

For the pin puller considered in the present study, the housing and the pin shaft are both made of 17-4pH stainless steel. The pin shaft mass M_s is 0.0144 kg. The initial internal volume of the expansion chamber V_0 is 650 mm^3, and the full stroke of the pin shaft is 9.2 mm. The shear pin is made of 6061-T6 aluminum and has a diameter of 0.8 mm. The stud at the locking mechanism is made of STS 304 stainless steel. The pyrotechnic initiator contains $ZrKClO_4$ (zirconium–potassium perchlorate, ZPP) powder pressed onto the bridge wire. A stainless steel closure disk is welded to the end of a charge column in an initiator to guarantee a hermetic seal.

2.2 Performance Modeling and Its Validity

Equations describing the function of a pin puller are given in the form of the following ordinary differential equations (ODEs):

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

$$\frac{dP}{dt} = \frac{\eta_p\left[\gamma R_g T_f \dot{m}_{gen} - (\gamma-1)\left(PA_p - W_p\cos\theta\right)v_p\right] - P\left(A_b r_b + A_p v_p\right) - (\gamma-1)\dot{Q}_{loss}}{V} \tag{2}$$

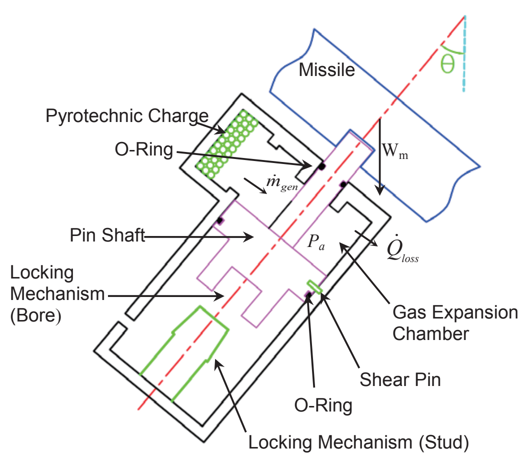

Fig. 1. A schematic of a newly developed pin puller.

$$\frac{dV}{dt} = A_b r_b + A_p v_p \tag{3}$$

$$\frac{de}{dt} = r_b \tag{4}$$

$$\frac{dv_p}{dt} = \frac{g}{W_p}\left(F_{pr} - F_{sh} - F_{or} - F_{ld} - F_{lm}\right) \tag{5}$$

$$\frac{dl}{dt} = v_p \tag{6}$$

Equations (1) and (2) govern the evolution of combustion product gases, Eq. (5) describes the pin shaft motion, and the remaining equations are related to geometric constraints. A set of six ODEs must be solved simultaneously using a numerical integration scheme, e.g., the fourth-order Runge–Kutta method. Detailed descriptions can be found in a previous report [15]. Comparisons between experimental and computational results are presented in Figs. 2 and 3. Fairly good agreement is observed, confirming that this model is adequate for simulating pin puller performance. It is important to note that accuracy of the performance model, i.e., how well it represents firing-test data, can affect the result of reliability estimation.

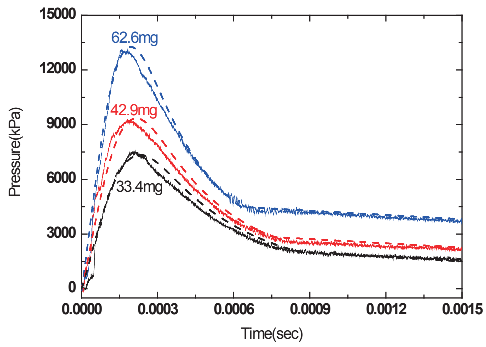

Fig. 2. Comparison of predicted (dashed lines) and measured expansion chamber pressure history [15].

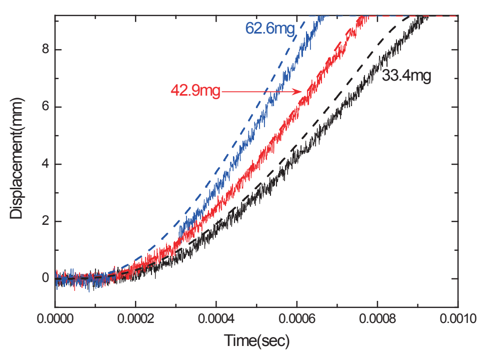

Fig. 3. Comparison of predicted (dashed lines) and measured pin shaft displacement versus time [15].

3. Simulation Model for Reliability

A simulation model for reliability was developed based on the stress–strength interference model widely used in probabilistic design. Let B and C be variables of stress and strength, respectively. In the stress–strength model, if $B > C$, i.e., if the stress exceeds the strength, failure occurs. Thus, failure can be expressed simply by a single variable, as in the following equation:

$$D = C - B \tag{7}$$

Here, neither B nor C is a point value; each is a random variable with a probability density function (*pdf*), as shown in Fig. 4. The overlapping region of the two *pdf*s, shaded in Fig. 4, is defined as failure, which corresponds to the unreliability Q:

$$Q = \Pr\left(B > C\right) = \Pr\left(D \le 0\right) \tag{8}$$

Because one minus Q equals the reliability of a device, the reliability R is given by all the probabilities that the strength exceeds the stress, or D is greater than zero. Hence the reliability can be obtained by the integration of the *pdf* of D, $f(D)$, from zero to infinity:

$$R = 1 - Q = \Pr\left(C > B\right) = \Pr\left(D > 0\right) = \int_0^{\infty} f(D)dD \tag{9}$$

Of the six ODEs that make up the performance model, Eq. (5) is the key in applying this concept to predicting the reliability of the pin puller. Successful functioning of the pin puller is defined as the pin shaft being retracted to the predetermined position. Successful retraction can only be achieved when the force generated by the combustion of the pyrotechnic charge is greater than the force consumed in overcoming the resistance to the movement of the pin shaft. That is, whether successful functioning of the pin puller is achieved depends on the competition of these two counteracting forces.

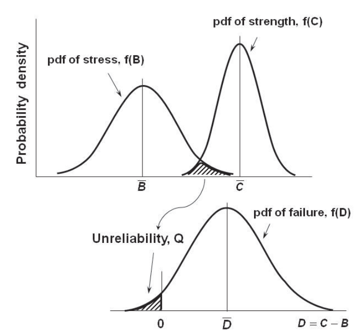

Fig. 4. The stress–strength interference model.

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The force generated by combustion is determined by two design parameters: the pin shaft's cross-sectional area, A_p, and the gas pressure produced by the combustion of pyrotechnic charges, P, which is expressed by the equation $F_{gen}=F_{pr}=P_{Ap}$. The force consumed by resisting movement of the pin shaft, F_{con}, is governed by various forces: F_{sh}, which is the force needed to cut off the shear pin; F_{or}, which is the friction force caused by the O-rings fitted onto the pin shaft; F_{ld}, which is the friction force at the contact surface between the retracting pin shaft and the hole of the object to be released (in this study, a missile); and F_{lm}, which is a locking force. The locking force referred to here is the force absorbed by the locking mechanism that is used to prevent rebound of the retracted pin shaft.

If we designate the generated force, F_{gen}, and the consumed force, F_{con}, as the strength and the stress in the model, respectively, then the variables C and B can be expressed as follows:

$$\begin{aligned} C &= F_{gen} = F_{pr} \\ B &= F_{con} = F_{sh} + F_{or} + F_{ld} + F_{lm} \end{aligned} \tag{10}$$

Therefore, according to the definition of Eq. (9), the reliability of the pin puller can be expressed as follows:

$$R = \Pr\left(F_{gen} > F_{con}\right) = \Pr\left(F_{pr} > F_{sh} + F_{or} + F_{ld} + F_{lm}\right) \tag{11}$$

The above model definition is not always sufficient to determine whether the pin puller performs well or not. This is because all the forces in Eq. (11) are a function of time t; that is, the magnitudes of the forces vary with time. In this respect, even though force is the main factor in the performance model calculation, force was not an appropriate performance variable for use in the current reliability study. Another performance variable is needed that can be quantified over the entire functioning period of the pin puller. Fortunately, through the performance model calculation mentioned earlier, we can calculate the forces as a function of time or displacement of the pin shaft (see Eq. (6)). Thus, the forces can be transformed into the form of either impulses (i.e., products of force and time) or energy (i.e., products of force and displacement). In this study, energy was selected as the performance variable. Consequently, the reliability of Eq. (11) can be rewritten as follows:

$$R = \Pr\left(E_{gen} > E_{con}\right) = \Pr\left(E_{pr} > E_{sh} + E_{or} + E_{ld} + E_{lm}\right) \tag{12}$$

where the subscripts are used in the same way as for the forces in Eq. (11).

The current model has the advantage that the variables needed to predict reliability can be easily obtained through performance calculations. In practice, it is not easy to obtain the five energy terms in Eq. (12) directly through experimental methods because the evolution of the forces, particularly as a function of displacement or time, is hard to measure. Furthermore, because each of the forces is related to more than one variable, too much effort would be required to examine the effects of the variables on each force even though the measurement were possible. For example, for $E_{pr}=\int F_{pr}\,dl=\int PA_p\,dl$, the pressure P is dependent on many other variables or parameters associated with performance or operating conditions, such as the amount of pyrotechnic charge, the volume of the combustion chamber, the burning rate of the pyrotechnics, the operating temperatures, and so on. However, in the present model calculation, the energies are easily computed regardless of how many implicit components being involved.

An additional advantage of this simulation model is that the *pdf*s of the variables of interest can be obtained easily. In a probabilistic approach, *pdf* information is indispensable, but obtaining this information can be difficult because of the large number of tests required. In the present study, the pdf information was synthesized easily using the Monte Carlo method. That is, the *pdf*s of the consumed energy and the generated energy were constructed by iterative calculation of the performance for input values randomly chosen from the distributions of the respective design parameters.

4. Simulation and Results

4.1 The General Concept of MC Simulation

Monte Carlo simulation is a computer-based sampling technique that is widely used in many fields. From a reliability evaluation point of view, the basic concepts of MC simulation method are as follows. Consider a random variable, Y, called the output variable of interest. Y is a known function of one or more other random variables, X_i, called input variables, which have known distributions, i.e., $Y=f(X_1,X_2,\cdots,X_k)$. Using a randomly drawn value of each of the input variables from their respective populations, one can calculate the resulting value of the output variable, y_j, from a given function of the form $y_j=f(x_{j;1},x_{j;2},\cdots,x_{j;k})$. This is called a trial or a sampling. Such a trial is repeated N times, yielding a set of sample data $\{y_1,y_2,\cdots,y_N\}$. With these resulting sample data, one can determine the distribution of Y or obtain probabilistic information of the distribution. Selecting random variables for a specified distribution is equivalent to selecting a sample from a population. Because this sampling is not restricted by interrelationships between the variables, MC simulation can be particularly useful in case where the output variable cannot be written as a closed-form expression of the input variables, as in the present study. For further details on MC simulation, see references [14, 20].

4.2 The Details of the MC Simulation Method

An MC simulation was conducted to estimate the reliability of the pin puller. The simulation procedure consists of the following four steps:

1) Generate values of the design parameters involved in Eqs. (1) to (6), according to their respective probability distribution functions.
2) Using the randomly generated values as the inputs, calculate the performance through the Runge–Kutta integration method.
3) Calculate the energies corresponding to the variables of B and C (or D) from the results of the performance calculation.
4) Repeat the steps above N times until the desired precision is obtained.

Information about the design parameters used as simulation inputs is provided in Table 1. Some of the design parameters, given in Table 1, cannot be shown explicitly in Eqs. (1) to (6), the details of which can be found in a previous article [15]. The random variables were assumed to be independent of each other, and their distributions were assumed to be normal. The two parameters of a normal distribution for each design parameter were determined using specified design values: the nominal value was used for the mean, and the tolerance value was used for the standard deviation, according to the so-called "three-sigma" rule that one half of the tolerance range is equal to three standard deviations, i.e.,$3\sigma=0.5\delta$ [16, 17]. For the weight of the pin shaft, for example, because the nominal value is 32 g and the tolerance is ± 0.05 g, the corresponding parameters of the normal distribution were taken to be a mean of μ=32 and a standard deviation of σ=0.05/3. This allocation of the standard deviation can be interpreted as our uncertainty with respect to the input variable.

4.3 Reliability Calculation Scheme

The MC calculations yield the probability distribution of the failure variable D as an output. Frequency histograms or density histograms give some idea of the shape of the output *pdf*. Goodness-of-fit tests can be used to determine how well the histograms represent the intended theoretical distribution. The reliability can be estimated by integration of the resultant *pdf*, *f(D)*, over the range of $D > 0$, as in Eq. (13). In the case of *f(D)* conforming to a normal distribution, the reliability is easily computed using the probabilistic information about the standard normal distribution, without performing the integration:

$$R=\int_0^\infty f(D)dD=\int_{Z_0}^\infty \phi(Z)dZ=1-\Phi(Z_0)=\Phi(-Z_0) \quad (13)$$

where $\phi(Z)$ is the *pdf* of the standard normal distribution, $\Phi(Z)$ is the cumulative distribution function, and Z is the standard normal variate. The integral's lower limit, Z_0, is equal to

$$-Z_0=\frac{\overline{D}}{s_{\overline{D}}} \quad (14)$$

where $\overline{D}$ and $s_{\overline{D}}$ are the mean and standard deviation, respectively, of D. This definition is often called the "reliability index" in structural design [18, 19].

When the *pdf* of D does not follow a normal distribution, the integration is not easy. In that case, the reliability can be estimated from the following equation based on the hit-or-miss method [20]:

Table 1. Design parameters used as the simulation inputs

Design Parameter	Symbol	Mean	Standard Deviation
Initial volume	V_i	0.539E-6 m^3	±0.00208
Pin outer diameter	d_o	17.165 mm	±0.025
Pin inner diameter	d_i	8.29 mm	±0.01
Pin weight	m_p	32 gram	±0.05
Pyrotechnic charge amount	m_{pc}	43.5 mg	±5
Burning rate constant	A	0.741	±0.3894
Burning rate exponent	N	0.190	±0.09179
Release point of missile	d_r	5.0 mm	±0.1
Start point of locking	d_l	7.7 mm	±0.2
Full stroke	S	9.2 mm	±0.2
Shear force	F_{sh}	12.5 kg$_f$	±1.019294
Load to pin friction Coef.	μ_{lp}	0.38365	±0.00966
Locking mechanism, F_{lm}	Y0	-28.47464	±11.77159
	A1	186.52577	±12.5655
	T1	0.09579	±0.01337
	A2	607.20012	±19.42515
	T2	1.72862	±0.16784

$$\hat{R} = \frac{1}{N}\sum_{i=1}^{N} I(D^{(i)} > 0) = 1 - \frac{1}{N}\sum_{i=1}^{N} I(D^{(i)} < 0) \quad (15)$$

where N is the number of iterations and $I(\cdot)$ is the indication function that takes a value of 1 when $D^{(i)}>0$ and takes a value of 0 otherwise in the i-th simulated result. As N increases, by the law of large numbers, the estimator converges to the true value. R in Eq. (13) and $\hat{R}$ in Eq. (15) are with the same meaning; but the hat in the latter case is used to emphasize estimated values that can be obtained from the simu lation data.

4.4 Reliability Simulation Results

4.4.1 Reliability calculation

Under the condition that the pyrotechnic charge weight is 43.5 mg, MC simulations were conducted for 12×10^6 iterations. Among the simulation results, B, C, and D are the variables of interest. The results are plotted in Figs. 5(a) and 5(b). The data are judged to be normally distributed without any goodness-of-fit test being conducted because they appear to closely conform to the theoretical normal distribution represented by the solid lines in Fig. 5. From Eq. (13), the reliability can be determined as follows:

$$R = \int_0^\infty f(D)dD = \Phi(3.958) = 0.99996 \quad (16)$$

For the same simulation results used in the above estimation, the reliability was estimated using Eq. (15). The number of failures (i.e., when $D < 0$) was 29 out of 12×10^6 trials, yielding

$$R = 1 - \frac{29}{12\times10^6} = 0.999997 \quad (17)$$

A small but non-negligible difference between the two results was found. This difference is related to the normal approximation used concerning the resultant distributions of B, C and D and to the inherent accuracy of the MC method. When the probability of failure is low, its value can be changed highly sensitively in the extreme tail portions of the distribution. Additionally, the accuracy of the MC method is not high. For example, in the present case, the failure probability is estimated at 2.4×10^{-6}. The standard error of the estimate is 4.5×10^{-7}, approximately one fifth of the estimated failure probability. The accuracy deteriorates as the failure probability decreases.

4.4.2 Effect of pyrotechnics weight on reliability

Reliability simulations were also conducted for different amounts of pyrotechnic charge. The number of iterations was N = 10,000 in each simulation. The results are listed in Table 2.

In the last column, the subscript number denotes the number of nines; for example, 0.9_67 means 0.9999997. The greater the amount of pyrotechnic charge is considered, the higher the reliability achieved is. As the amount of pyrotechnic charge increases, the generated energy increases proportionally, whereas the consumed energy is almost unchanged, making the difference between the two energies much larger. This can be interpreted, from the perspective of the probabilistic stress–strength model in Fig. 4, as an increase in the charge weight making the mean of the strength distribution move farther to the right, decreasing the overlapped area of the stress and strength distributions. Alternatively, as the charge weight increases, the mean of the failure distribution moves to a position farther away from the line of D = 0, which results in a higher reliability. It should also be noted in the distribution of C, while the value of the mean increases in proportion to the charge weight, the standard deviation is almost unchanged. Figure 6 illustrates the relationship between the charge weight and the reliability.

4.4.3 Sensitivity Analysis

A sensitivity analysis was performed to determine

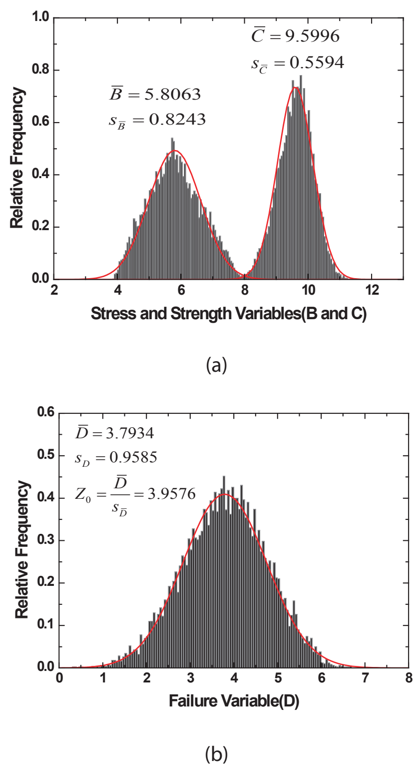

Fig. 5. Reliability simulation results: (a) stress–strength distributions and (b) failure distribution.

which design parameters most affect the reliability of the pin puller. The contribution of each input design parameter to the output failure variable, *D*, was analyzed by means of a Pearson correlation analysis[21], with 10,000 sample data points, each one representing values of the 13 design parameters and D. In the sensitivity analysis, correlation between the design parameters was not taken into account, i.e., the association between each design parameter and D was considered separately. A correlation coefficient is used to define the strength and direction of a linear relationship between two variables. A correlation coefficient value close to 1 or -1 indicates that an input variable strongly influences the output.

In the present study, a design parameter with a correlation coefficient greater than 0.15, regardless of whether the sign is positive or negative, was considered an indicator that the parameter has a significant influence on the reliability. Of the 13 design parameters considered, the following six parameters were identified as being the most influential: the amount of pyrotechnics (m_{pc}), the burning rate constant (A), the burning rate pressure exponent of the pyrotechnics (n), the absorbing force by the locking mechanism (F_{lm}), and the initial (d_l) and final (S) positions of the locking mechanism. The first three parameters are related to the pyrotechnics, and the remaining parameters are related to the locking mechanism.

Simulations were conducted with the six parameters identified as being most influential, with only one parameter at a time varied to check its impact on the reliability. Each parameter was varied such that while the mean of the parameter remained the same, its standard deviation was increased to twice that of the reference value. The reference values for the parameters are listed in Table 1. For example, the standard deviation of the pyrotechnic charge weight was changed from ±5 mg to ±10 mg in the simulation, while the values of the other design parameters remained the same. These increases in the variance of the input design parameters significantly contributed to the increase in the variance of the output, *D*, reducing the reliability. The simulation results, showing the impact of each parameter on the reliability, are summarized in Fig. 7. As the figure shows, the start point of locking, d_l, and the full stroke, S, were the most influential parameters in the reliability.

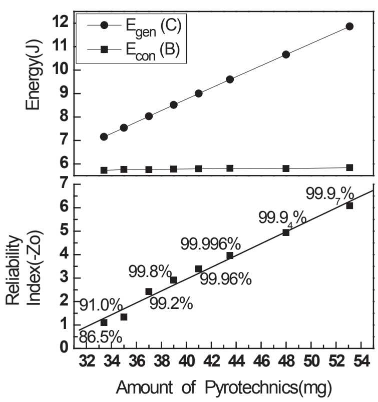

Fig. 6. The relationship between the amount of pyrotechnic charge and the reliability (solid lines are visual aids).

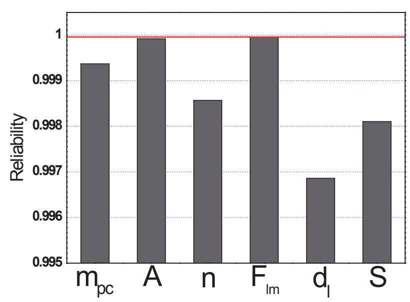

Fig. 7. Impact of each parameter on the reliability (the horizontal solid line is a reference for R=0.99996).

Table 2. Simulation results for different amounts of pyrotechnic charge

Charge Weight (mg)	$C(E_{gen})$		$B(E_{con})$		$D(=E_{gen}-E_{con})$		$-Z_0$	Reliability
	$\overline{C}$	$s_{\overline{C}}$	$\overline{B}$	$s_{\overline{B}}$	$\overline{D}$	$s_{\overline{D}}$		$\Phi(-Z_0)$
23.7	4.628	0.500	4.597	0.472	0.031	0.973	0.032	0.5127
33.4	7.152	0.499	5.721	0.795	1.431	1.292	1.101	0.8646
35	7.535	0.513	5.764	0.812	1.771	1.323	1.338	0.90958
37	8.029	0.517	5.755	0.831	2.275	0.940	2.420	0.99190
39	8.519	0.525	5.778	0.829	2.741	0.940	2.916	0.99827
41	9.002	0.537	5.792	0.820	3.210	0.945	3.395	0.99961
43.5	9.599	0.559	5.806	0.824	3.793	0.959	3.958	0.99996*
48	10.659	0.602	5.802	0.830	4.857	0.983	4.942	0.9_67
53.1	11.865	0.648	5.837	0.827	6.028	0.991	6.084	0.9_96

(*This value is calculated from the simulation result of N=12 x 10^6 iterations)

5. Discussion

5.1 Bridging performance modeling and reliability

Important issues in the development of one-shot devices are knowing how reliable the device is and knowing which design parameters most affect its reliability. For that matter, one needs to be able to identify and quantify the strength (or capability) and the stress (or burden) on the functioning of the device. In reality, it is very difficult to obtain such information because of the destructive behavior and complicated operating mechanisms of such devices. The reliability can only be assessed by sampling some of the devices and fully testing them, which yields a success rate. However, this approach requires a large number of firing tests to obtain success (or failure) data, particularly with statistical significance. This necessitates a new way to evaluate the reliability of such devices without expensive collection of firing data.

Adopting the stress–strength model described in this paper enables us to evaluate the reliability or design adequacy of the pin puller. In the present study, the capability is defined as the energy generated by the combustion of pyrotechnics, and the burden is defined as the energy consumed by resistance to the movement of the pin shaft to the predetermined position. However, determining the values of these energies through conventional firing tests with sample pin pullers would be impractical. This is because firing tests only provide information such as the pressure within the chamber and the distance that the pin shaft moves; they do not provide information directly related to the energies of interest. In contrast, if we use the performance model, information on these variables can easily be obtained from the calculation results. That is, the generated and consumed energies can be directly identified and quantified from each piece of information related to them in the performance model. It is important to note that the approach proposed provides a clear understanding of how well a particular pin puller design will perform prior to actual use. This is a major advantage of the proposed approach.

5.2 Safety Factor and Reliability

In deterministic design approaches, a safety factor is often used as a measure of the adequacy of a particular design. The safety factor is defined as the ratio of the strength (C) to the stress (B) of a design. If the safety factor is greater than one, the design functions successfully. Hence, a safety factor value greater than one is sought to account for uncertainties in the design and fabrication processes, usage, and degradation. In the case of a pin puller, if the generated energy (C) and the consumed energy (B) are known quantitatively, we can predict whether the pin puller will perform successfully through the use of a safety factor. Here, let us use the central safety factor, $\frac{\overline{C}}{\overline{B}}$, which is defined as the ratio of the mean values of C and B, despite the fact that a deterministic approach neglects the fact that C and B are distributed.

Using the data in Table 2, we can establish the relationship between the safety factor and the reliability, which is illustrated in Fig. 8. The safety factor is linearly related to the reliability. It should be noted that for the amount of pyrotechnics considered, in all cases, the safety factors are greater than one, meaning that the pin puller does not reach its maximum stress. From a deterministic perspective of the safety factor, therefore, the design of the pin puller is considered acceptable even in case of a 23.5 mg pyrotechnic charge. From a probabilistic perspective, however, the reliability was calculated to be 0.51, which is equivalent to a reliability index of 0.032, as shown in Table 2. This comparison shows that the safety factor is an inadequate measure in that it does not provide quantitative information on how well the pin puller will function. In the stress–strength model, the reliability depends on the overlap of the distributions of C and B. A decrease in the tail overlap area, which corresponds to an increase in the reliability, can be accomplished by either increasing the difference between the distribution means or reducing the dispersions of the distributions. The former can be accomplished by increasing the amount of the pyrotechnic charge. The latter can be accomplished by controlling the statistical variation of the design parameters. However, the former method of increasing the reliability—using a greater amount of pyrotechnic charge—may not be adequate because an unnecessarily excessive pyrotechnic charge may cause such adverse effects as high pyrotechnic

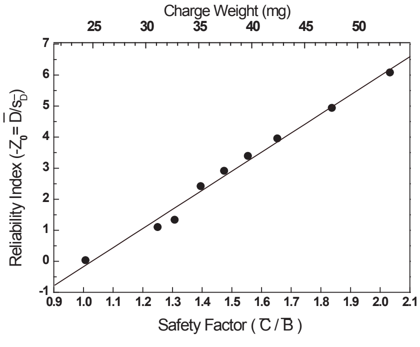

Fig. 8. The relationship between the safety factor and the reliability (the solid line is a visual aid).

shocks to the system in which the pin puller is used. No matter how far apart the mean values are (i.e., no matter how large the safety factor is), there could be an overlap between the distributions of *C* and *B* because of their dispersions. If possible, therefore, controlling the statistical variations of the design parameters is a better approach to decreasing the overlap of the distributions. The smaller the distribution dispersions are, the smaller the tail overlap can be. The target reliability of the pin puller can be achieved by a combination of selection of the proper amount of pyrotechnic charge and careful control of the variations of the design parameters.

6. Conclusions

It is usually not feasible to evaluate the reliability of pyrotechnic devices by testing because of the one-shot nature of such devices. Realistically, there is no way to guarantee the reliability of such devices; their probability of success can only be estimated from firing tests of sampled devices. However, such tests are almost impossible in practice because of the large number of tests required to determine the probability of success with statistical significance. This paper describes an approach to evaluating the reliability of one-shot devices that bridges performance modeling and reliability. This approach involved predicting reliability using a stress–strength model. Information on the variables that influence the stress and strength of the system of interest can be identified and quantified easily from the model performance, even though they can rarely be obtained from firing tests because of their implicit attributes. The probability densities of the variables needed to predict the reliability can also be obtained by Monte Carlo simulation, taking into account the statistical variations of the design parameters that are involved in the performance model. This approach enables us to know, at the beginning of the development phase of a pin puller, what its reliability is and which design parameters should be controlled to achieve the target reliability without expensive firing tests.

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