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Reliability Analysis of Retracting Actuator with Multi-State Based on Goal Oriented Methodology

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Abstract: In order to conduct effective reliability analysis of retracting actuator with multi-state (success state, safety failure state and action failure state), we redefine type-3 operator in goal oriented (GO) method to describe three states of main charge of retracting actuator and improve type-15 operator in GO method to describe the logic relations of multi-state output. The quantitative and qualitative reliability analyses of retracting actuator are made based on GO method in this paper. The system state probability of retracting actuator is obtained through quantitative analysis, and its weakness is found through qualitative analysis. The analysis results show that GO method is effective to improve the reliability of retracting actuator, and this method is also feasible for reliability analysis of other complicated initiating explosive systems.
Key words: retracting actuator, goal oriented (GO) methodology, operator, multi-state, reliability analysis
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0 Introduction

Retracting actuator is a kind of device in which pyrotechnic is ignited by electrical energy to produce high-temperature and high-pressure gas, and a piston is pushed to achieve release function. Such device has been widely used in spacecraft and other precision-guided munitions. More applications of retracting actuator and its reliability are required increasingly. Reliability analysis is an important measure to ensure retracting actuator to achieve high reliability. Currently, fault tree analysis (FTA) and failure modes & effects analysis (FMEA) are commonly used in system reliability analysis, but the two methods have limitations for reliability analysis of retracting actuator with multi-state (success state, safety failure state and action failure state). Goal oriented (GO) methodology is a success-oriented method for system reliability analysis[1]. It has stronger adaptability for reliability analysis of system with multi-state than FTA and FMEA. We use GO method to make qualitative and quantitative reliability analyses for retracting actuator in this paper.

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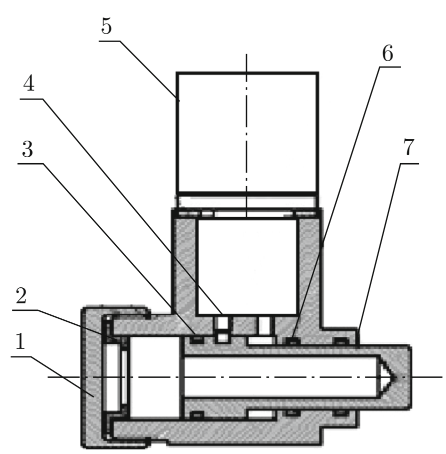
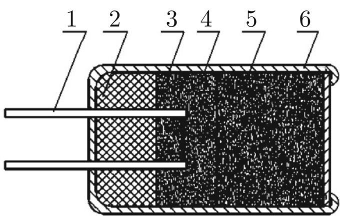
1 Reliability Analysis of Retracting Actuator Based on GO Method

A retracting actuator is shown in Fig. 1. The detonator is electrified to make retracting actuator act,



1—Screw cap, 2—Buffer ring, 3—Seal II, 4—Stopper pin
5—Detonator, 6—Seal I, 7—Piston
Fig. 1 Structural diagram of a retracting actuator

and high-temperature high-pressure gas generated by combustion of charge goes into the cavity of seal housing assembly through a fire hole. The stopper pin is cut off while the gas pressure acts on the piston, and the piston retracts in the axial direction. At last, the release function is achieved. The work process of retracting actuator can be divided into two sections. One is input section and the other is output section. The former section means detonator ignition and the latter section means piston retraction. The detonator in the retracting actuator is bridge-wire electric explosive device (EED)[2], as shown in Fig. 2.



1—Foot line, 2—Electrode plug
3—Ignition powder, 4—Bridge-wire
5—Primary explosive and the main charge, 6—Shell

Fig. 2 Structural diagram of bridge-wire EED

When detonator is successfully ignited and the stopper pin is successfully cut off, the retracting actuator succeeds. When the detonator cannot be properly ignited or explodes to damage its housing or the stopper pin is not completely cut off, the retracting actuator fails. There are two different failure states: function failure and safety failure. Therefore, the retracting actuator has three states: success state, safety failure state and function failure state.

1.1 Establishing GO Model of Retracting Actuator

The workflow diagram of a retracting actuator is shown in Fig. 3.

Four types of operators, which are type-1, type-3, type-5 and type-15, are selected according to the state of each unit of the retracting actuator, as shown in Fig. 4[3]. In Fig. 4, S represents the system input, R represents the system output, and the figure represents the type of operator. Then, each operator which is corresponding to each unit of the retracting actuator is described in detail. If the operator cannot meet requirements, then it will be developed in this paper.

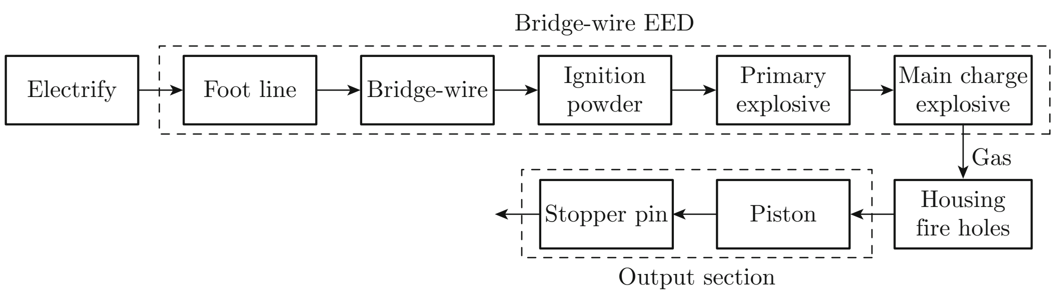


Fig. 3 Flowchart of a retracting actuator

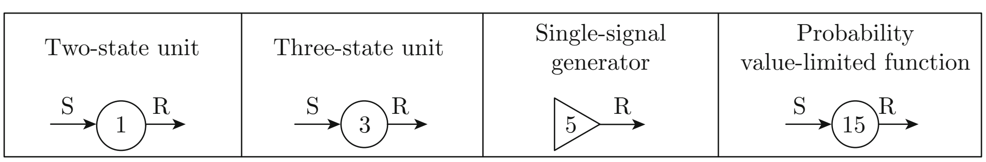


Fig. 4 GO operator schematic

Because foot line, bridge-wire, ignition powder, primary explosive, fire hole and stopper pin generally have two states, which are success state and failure state, type-1 operator is selected for them.

Type-5 operator, a signal generator, is selected to describe direct current (DC) input signal of retracting actuator and the operator has three states, which are success state, abnormal current state and failure state.

If main charge succeeds, it should meet two requirements: ① high-temperature high-pressure gas generated by the combustion of main charger goes into the cavity of the seal housing through housing fire holes and makes stopper pin cut off; ② the housing cannot be damaged.

When Requirement ① is not met, the main charge is thought to be function failure. When Requirement ② is not met, main charge is thought to be safety failure. These two failures are different. So, the main charge has three states and they are success state, function failure state and safety failure state. The improved type-3 operator is selected for main charge with three states.

Although the existing type-3 operator can be used to describe three states, State 0 (advance), State 1 (success) and State 2 (failure), it cannot be directly used to describe main charge with three states, and thus the type-3 operator should be improved. Now, the type-3 operator is redefined to describe three states of main charge. These three states are State 1 (success), State 2 (function failure) and State 3 (safety failure). The values of these three states are represented as $V_C = 1$, 2, 3, respectively. Their probabilities are represented as $P_C(1)$, $P_C(2)$ and $P_C(3)$, respectively. The new arithmetic rule of type-3 operator is shown in Table 1, where V_S and V_R represent the state values of input signal and output signal of operator.

Table 1 New type-3 operator operational rule

V_S	V_C	V_R
1	1	1
not 1	1, 2, 3	2
1	3	3

According to the operational rule of new type-3 operator, its state probabilities are calculated as

$$P_R(1) = P_S(1)P_C(1),$$
$$P_R(2) = [1 - P_S(1)][P_C(1) + P_C(3)] + P_C(2),$$
$$P_R(3) = P_S(1)P_C(3),$$

where, $P_S(1)$ represents probability of state $V_S = 1$; $P_R(1)$, $P_R(2)$ and $P_R(3)$ respectively represent probability of state $V_R = 1, 2, 3$.

High-temperature high-pressure gas generated by combustion of charge is divided into two sections to overcome two kinds of resistances. One is used to overcome the friction of the piston which is exerted positive pressure on the radial direction, and the other is used to overcome the resistance of movement of the piston inside the retracting actuator[4]. Therefore, State 1 can be defined as success state when the gas pressure is larger than the resistance and energy generated by gas is larger than the energy required to overcome the resistance of piston. State 2 can be defined as failure state when the gas pressure is less than or equal to the resistance of the piston and its energy cannot overcome the resistance of piston and the stopper pin cannot be cut off.

In this case, the output of retracting actuator is determined by comparing the input pressure with resistance. So, the gate operator which limits the probability (improved type-15 operator) can be selected to describe the retracting actuator.

$$V_R = \begin{cases} V_{S1} + Y_i, & 0 \leqslant V_{S1} + Y_i < 2 \\ 0, & V_{S1} + Y_i < 0 \\ 2, & V_{S1} + Y_i \geqslant 2 \end{cases},$$

where $V_{S1}(1, 2)$ represents the input state value (1-success state, 2-failure state), and Y_i represents the gain value of output signal state. Operational rules of the above operator are shown in Table 2, where $V_{S2}(1, 2)$ represents the state value of resistance (1-success state, 2-failure state), and X_i represents the difference between the two state values of V_{S1} and V_{S2}.

Table 2 Operational rules of new type-15 operator

V_{S1}	V_{S2}	X_i	Y_i	V_R
1	1	0	0	1
2	1	1	1	2

According to the operational rules of new type-15 operator, its state probabilities are calculated as

$$P_R(1) = P_{S1}(1), \quad 0 \leqslant V_{S1} + Y_i < 2,$$
$$P_R(2) = P_{S1}(2), \quad V_{S1} + Y_i \geqslant 2,$$

where $P_{S1}(1, 2)$ represents probability of $V_{S1}(1, 2)$. The GO model of retracting actuator is established according to its working process and appropriate operator, as shown in Fig. 5. The former number in an operator represents its type, and the latter one indicates its serial number. The number on signal flow indicates its serial number.

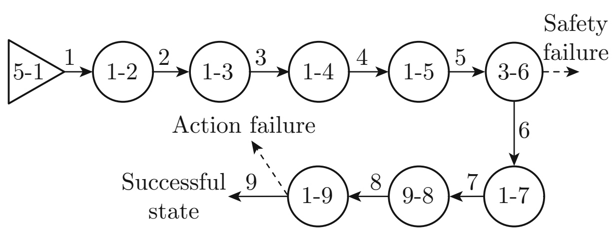


Fig. 5 GO model of a retracting actuator

1.2 Quantitative Analysis of Reliability for Retracting Actuator Based on GO Method

Because the probability formula algorithm can be used to calculate directly the state probability of output signal from the state probability of operator and its input signal, state combinations do not need to be listed, and the probability formula algorithm can greatly simplify the quantitative calculation of GO method. So, the probability formula algorithm is selected to conduct GO operations.

Based on the given state probability of each component, the state probability of retracting actuator can be calculated.

Suppose $P_{Si}(j)$ represents the state probability of signal flow i, and $P_{Ci}(j)$ represents the state probability of operator i, $i = 1, 2, \cdots, 9$. Suppose j represents their state, $j = 0$ means abnormal state, $j = 1$ means the success state, $j = 2$ means failure state i.e. action failure, and $j = 3$ means failure state i.e. safety failure. Suppose $P_{\mathrm{S6}}(3)$ is state probability of safety failure of retracting actuator, $P_{\mathrm{S9}}(1)$ is its success probability, and $P_{\mathrm{S9}}(2)$ is its probability of action failure.

State probabilities of each unit in retracting actuator are listed in Table 3. There are three states corresponding to DC input signal (0-abnormal, 1-success, and 2-failure). Too large or too small DC currents are called abnormal currents. The bridge-wire of detonator can be broken because of too large current, and action failure of retracting actuator will occur. The detonator does not work because of too small energy produced by too small current. Therefore, both the abnormal current and failure of current are corresponding to the failure state of retracting actuator.

Table 3 Reliability data of operational character of the retracting actuator

Serial number	Type	Unit name	Probability		
			State 1	State 2	Other State
1	5	DC-powerd	0.999 92	0.000 03	0.000 05
2	1	Foot line	0.999 97	0.000 03	—
3	1	Bridge wire	0.999 99	0.000 01	—
4	1	Ignition powder	0.999 98	0.000 02	—
5	1	Primary explosive	0.999 98	0.000 02	—
6	3	Main charge	0.999 92	0.000 05	0.000 03
7	1	Fire hole	0.999 99	0.000 01	—
8	9	Piston	—	—	—
9	1	Stopper pin	0.999 97	0.000 03	—

$$
\begin{aligned}
&P_{\mathrm{S1}}(0) = P_{\mathrm{C1}}(0),\\
&P_{\mathrm{S1}}(1) = P_{\mathrm{C1}}(1),\\
&P_{\mathrm{S1}}(2) = P_{\mathrm{C1}}(2),\\
&P_{\mathrm{S2}}(0) = P_{\mathrm{S1}}(0)P_{\mathrm{C1}}(1),\\
&P_{\mathrm{S2}}(1) = P_{\mathrm{S1}}(1)P_{\mathrm{C2}}(1),\\
&P_{\mathrm{S2}}(2) = P_{\mathrm{S1}}(2)P_{\mathrm{C1}}(1) + P_{\mathrm{C2}}(2),\\
&P_{\mathrm{S3}}(0) = P_{\mathrm{S2}}(0)P_{\mathrm{C3}}(1),\\
&P_{\mathrm{S3}}(1) = P_{\mathrm{S2}}(1)P_{\mathrm{C3}}(1),\\
&P_{\mathrm{S3}}(2) = 1 - P_{\mathrm{S3}}(0) - P_{\mathrm{S3}}(1),\\
&P_{\mathrm{S4}}(1) = P_{\mathrm{S3}}(1)P_{\mathrm{C4}}(1),\\
&P_{\mathrm{S4}}(2) = P_{\mathrm{S3}}(2)P_{\mathrm{C4}}(1) + P_{\mathrm{C4}}(2),\\
&P_{\mathrm{S5}}(1) = P_{\mathrm{S4}}(1)P_{\mathrm{C5}}(1),\\
&P_{\mathrm{S5}}(2) = P_{\mathrm{S4}}(2)P_{\mathrm{C5}}(1) + P_{\mathrm{C5}}(2),\\
&P_{\mathrm{S6}}(1) = P_{\mathrm{S5}}(1)P_{\mathrm{C6}}(1),\\
&P_{\mathrm{S6}}(2) = [1 - P_{S5}(1)][P_{\mathrm{C6}}(1) + P_{\mathrm{C6}}(3)] + P_{\mathrm{C6}}(2),\\
&P_{\mathrm{S6}}(3) = P_{\mathrm{S5}}(1)P_{\mathrm{C6}}(3),\\
&P_{\mathrm{S7}}(1) = P_{\mathrm{S6}}(1)P_{\mathrm{C7}}(1),\\
&P_{\mathrm{S7}}(2) = P_{\mathrm{S6}}(2)P_{\mathrm{C7}}(1) + P_{\mathrm{C7}}(2),\\
&P_{\mathrm{S8}}(1) = P_{\mathrm{S7}}(1), \quad 0 < V_{\mathrm{S7}}(1) + Y_1 = 1 < 2,\\
&P_{\mathrm{S8}}(2) = P_{\mathrm{S7}}(2), \quad V_{\mathrm{S7}}(2) + Y_2 = 3 > 2,\\
&P_{\mathrm{S9}}(1) = P_{\mathrm{S8}}(1)P_{\mathrm{C9}}(1),\\
&P_{\mathrm{S9}}(2) = P_{\mathrm{S8}}(2)P_{\mathrm{C9}}(1) + P_{\mathrm{C9}}(2).
\end{aligned}
$$

According to the above operations, we can get

$$
\begin{aligned}
P_{\mathrm{S9}}(1) = {} & P_{\mathrm{C1}}(1)P_{\mathrm{C2}}(1)P_{\mathrm{C3}}(1)P_{\mathrm{C4}}(1)P_{\mathrm{C5}}(1)\times\\
& P_{\mathrm{C6}}(1)P_{\mathrm{C7}}(1)P_{\mathrm{C9}}(1) = 0.999\,72,\\
P_{\mathrm{S6}}(3) = {} & P_{\mathrm{C1}}(1)P_{\mathrm{C2}}(1)P_{\mathrm{C3}}(1)P_{\mathrm{C4}}(1)P_{\mathrm{C5}}(1)P_{\mathrm{C6}}(3) \approx\\
& 0.000\,03,\\
P_{\mathrm{S9}}(2) = {} & \{[1 - P_{\mathrm{C1}}(1)P_{\mathrm{C2}}(1)P_{\mathrm{C3}}(1)P_{\mathrm{C4}}(1)P_{\mathrm{C5}}(1)]\times\\
& [P_{\mathrm{C6}}(1) + P_{\mathrm{C6}}(3)] + P_{\mathrm{C6}}(2)\}P_{\mathrm{C7}}(1)P_{\mathrm{C9}}(1)+\\
& P_{\mathrm{C7}}(2)P_{\mathrm{C9}}(1) + P_{\mathrm{C9}}(2) \approx 0.000\,25.
\end{aligned}
$$

1.3 Qualitative Analysis of Reliability of Retracting Actuator

To determine one-order cut set by qualitative analysis, we assume that success probability of a not-logical operator among all of GO operators is 0. If the system success probability is 0, the operator must be one-order cut set. Two-order and three-order cut sets can be obtained similarly. There are 9 operators in retracting actuator. If any operator fails, the system fails. So, all 9 operators are one-order cut sets of the retracting actuator. The weak link of the system can be found by minimum cut set analysis of system and it can provide guidance direction for improving the reliability of retracting actuator. The sum of probability of all minimum cut sets of the retracting actuator is 0.000 28 and the failure probability of retracting actuator based on GO method is 0.000 25. The result by GO method is correct and GO method is applicable for reliability analysis of retracting actuator.

2 Analysis Result

The main function of retracting actuator is to cut stopper pin and retract piston. The results of its reliability analysis are shown in Table 4. The system success probability is the state probability of output number 9. There are two failure states and they are safety failure and action failure.

Table 4 Result of reliability analysis of the retracting actuator

Serial number	System state	State probability	Component state
1	Success	0.999 72	All components succeed
2	Action failure	0.000 25	Any one component fails
3	Safety failure	0.000 03	—

The safety failure and action failure probability of retracting actuator can be simultaneously obtained by GO method while the only total failure probability can be obtained by FTA because the multi-state problem cannot be solved with FTA. According to the analysis results of GO method, some measures can be adopted to prevent the action failure and safety failure of retracting actuator.

3 Conclusion

GO method is one kind of the success-oriented reliability analysis methods with a simple process of building model. In this paper, the qualitative and quantitative analyses of retracting actuator based on GO method are conducted. The analysis results show that GO method is applicable for the reliability analysis of retracting actuator with multi-state. The method can be used in the reliability analysis of other pyrotechnics systems.

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