Functional Reliability Evaluation for Explosive Logic Network Based on Failure Analysis

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***Abstract*—As a new application technology of burst control, the explosive logic network (ELN) and its functional realization play critical roles in the areas of weapon system (such as missiles and torpedoes) and aerospace, as well to determine the reliability and safety for initiating explosive devices. This paper investigates the failure models and mechanism of ELN from the perspective of failure analysis and reliability engineering, as well combine the method of performance design and analysis, which are of great significance to carry out its functional reliability evaluation and health status assessment accordingly. Firstly, taking the ELN with two-input-four-output into account, we discuss its failure modes and failure factors based on its structural and functional properties, then establish the fault tree model for qualitative analysis. Secondly, considering some uncertainties inherent in a certain size parameters, we calculate the reliability window of the gap null gate, in term of probabilistic model and quantitative method so as to obtain the reliability of the gap null gate. Meanwhile, referring to estimated accuracy, we introduced the H-Bayes method in the field of ELN system and initiating explosive devices. After that, the environmental monitoring data is applied to health assessment system for ELN. Moreover, when it comes to merging a variety of condition assessment information of ELN's health level, we adopted the D-S evidential approach in information fusion for initiating explosive devices under shock conditions and electromagnetic interference. As far as the ELN is concerned, we find that: (1) Initiating explosive devices such as ELN are easily affected by environmental factors. The storage state described as storage life should be an important health indicator of ELN, which demands an effective evaluation strategy for the security and reliability considerations. (2) The functional reliability for complex ELN systems should be carried out by integrating multiple performance parameters into the evaluation method. (3) Along with three main indicators, namely, test information index, historical information index and monitoring information index, such information as polymorphism and relationship between quantitative and qualitative information should not be ignored.**

Keywords-explosive logic network (ELN); functional reliability; failure analysis; evidential information fusion

I. INTRODUCTION

The explosive logic network (ELN) is a kind of explosive trains which is realized by the unconventional detonating characteristics of explosives. It is composed of many kinds of explosive component and the input and output of initiating explosive device, which can achieve the detonation control functions such as delayed detonation and directional detonation. The ELN was first designed with the explosive logic null gates to achieve its functions by input from detonation signal [1]. As an important core technology of military equipment, ELN system plays a very important role in the reliability and security of the whole weapon system.

In the face of the small sample reliability evaluation of initiating explosive devices, Bement and Multhaup [2] put forward a statistical method to evaluate reliability of initiating explosive devices from the point of energy with less than 20 test samples for predicting the high reliability of pyrotechnics. Arul et al. [3] proposed a response surface method for computing the functional reliability. However, the theoretical details of the above research has not been made public for secrecy reasons which increased the difficulties for further applications.

A method named as functional reliability analysis has thus been brought forth to address the problems of correlation, polymorphism, non-monotonicity and fault tolerance in the complex weapon equipment systems, considering performance parameter indicators and the physics of failure for components when lack of reliability data [4]. Compared with the existing ELN research by describing the performance status using field data and sampling methods, the method of functional reliability analysis adopts statistical models and experimental data to describe performance status and failure mechanism, making full use of all kinds of information.

In this paper, starting from presenting the functional requirements and structural characteristics of ELN systems, the failure mechanism analysis is carried out based on explosion propagation theory for the ELN with two-input-four-output. The third part is to evaluate the functional reliability of ELN system using small sample method. In the fourth part, the framework of health evaluation for initiating explosive devices and ELN is constructed and the assessment methods of health conditions for ELN system with multi-source information is proposed.

II. FAILURE MECHANISM AND FAILURE MODES ANALYSIS OF ELN SYSTEMS

Compared with structural reliability, the theory of functional reliability pay more attention to functional failure

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process and the information changes during various system status [5]. In this section, the failure mode of explosive logic network is mainly studied based on function failure state description and detonation wave propagation theory, and the invalidation factor of internal and external uncertainty factors is also analyzed, and then we conduct the fault tree to explore the key factors which causes the failure of the explosive logic system, in order to further study of functional characteristics and storage health state level.

A. the failure modes and failure factors of ELN

For the research of ELN system, the function and security of ELN need to be discussed in terms of its functional status and the change of disseminate information. For example, the most basic module in a single logical network is the ELN with two-input-one-output. It will produce output only when the inputs detonate in a specific order and within a predetermined time window. Otherwise, the system has not any output. The failure modes of ELN are collected and analyzed and the internal and external factors are analyzed, as shown in Table I.

As shown in Table I , the failure factors of ELN are mainly divided into internal factors and external uncertain factors. The internal factors mainly focus on two aspects: the groove structure design of substrate and the performance of boaster explosive. The external uncertain factors mainly include the environmental uncertain factors and the artificial uncertain factors, among which the classification of environmental uncertain factors is shown in Fig. 1.

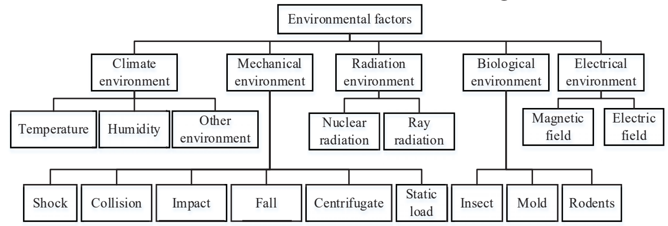


Figure 1. Classification of Environmental Factors

B. Functional Reliability Analysis based on FTA

Based on the analysis of the failure mechanism mentioned above, we obtain the failure factors associated with the ELN system as shown in Table II. Fig. 2 shows that the number of minimum cut sets is 19.

TABLE I. FAILURE MODE OF ELN

	Failure types	***Failure modes***	***Detailed classification of failure modes***
Function failure	Input function failure	Ammunition failure	Detonator failure
		Detonated accidently	Thermal initiation, shock and vibration, etc.
	Explosive propagation function failure	Excessive loss of energy transfer	The detonator velocity is reduced, The energy transfer channel is blocked, etc.
		Flameout	Explosive flameout, Explosive logic null gate failure, etc.
		The time of action is over ranged	The time of action is too long, The delay time is too short, etc.
	Output function failure	No output	No work output
		Insufficient output capacity	Insufficient explosive power, etc.
		Excessive output capacity	The part structure is destroyed, The delay time is interfered, etc.
Safety failure	Environmental safety	System safety is affected	Detonated accidently, The structure is destroyed
	Usage Safety		

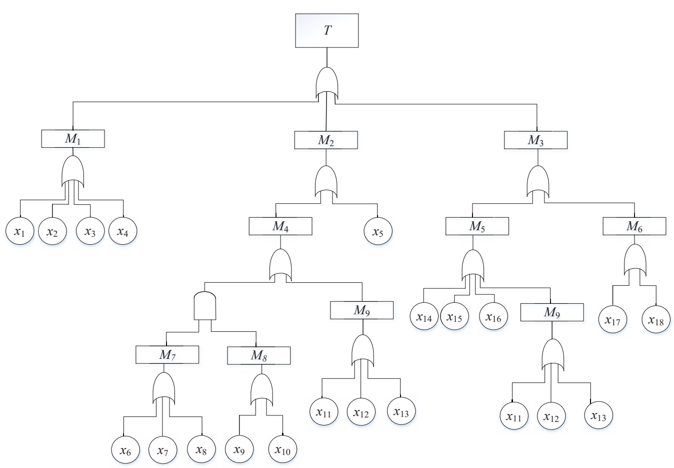


Figure 2. Fault Tree of ELN System

It could be concluded from the ELN failure tree that there are 18 elementary events which may lead to the top event. These elementary events mainly come from the design of ELN, the stimulation from the external environment and manual operation and these are the important factors that affect the reliability and security of ELN.

C. Measures to Improve The Reliability of ELN System

Based on the above analysis of ELN system, three measures can be taken to improve the reliability and security of ELN system: 1. choose the boaster explosive strictly; 2. design the logical network structure rationally; 3. check the storage environment regularly.

III. FUNCTIONAL RELIABILITY EVALUATION OF ELN BASED ON HIERARCHICAL BAYES ESTIMATION

The ELN has no explicit performance parameters, so it is impossible to estimate the functional reliability of ELN from the angle of performance design and there is seriously lack of reliability data. Since the ELN system is a one-time product, and the individual is independent of each other and obeys the binomial distribution, we adopt Bayes method to evaluate the functional reliability of ELN.

A. Bayes Evaluation

In the same sample size, Bayes estimation method can greatly improve the calculation accuracy, effectively reduce the sample size and save costs. Its mathematical formula can be expressed as:

$$p(\theta \mid X)=[\pi(\theta)L(X \mid \theta)]\Big/[\int \pi(\theta)L(X \mid \theta)d\theta]. \qquad (1)$$

In (1), $\pi(\theta)$ is a priori distribution of the parameter θ, $L(X \mid \theta)$ is likelihood function, which describes the sample's information, $p(\theta|X)$ is the posterior distribution of parameter θ.

In order to solve the problem of hyper parameter's selection and to obtain more accurate estimate, reference [6] uses the method of constructing Hierarchical Bayes to obtain the values of the hyper parameter *a* and *b*.

TABLE II. ANALYSIS ON FAILURE FACTORS OF ELN

No.	Event description	No.	Event description
T	ELN failure	x_5	Substrate constraints are too strong
M_1	ELN structural design is unreasonable	x_6	Low density of explosive
M_2	Material unqualified environment factors	x_7	Explosive size is small
M_3	Uncertainty factors	x_8	Explosive pool height is low
M_4	The sensitivity of explosive is low	x_9	The weight of explosive is insufficient
M_5	Environmental factors	x_{10}	The particle size of explosive is unreasonable
M_6	Artificial factors	x_{11}	High temperature
M_7	The detonator velocity is reduced	x_{12}	High humidity
M_8	Detonation wave pressure is low	x_{13}	Mold
M_9	Poor storage environment	x_{14}	Mechanical shock
x_1	Groove size is too small	x_{15}	Poor electrical environment
x_2	The degree of crossroad is unreasonable	x_{16}	Strong radiation
x_3	Null gate failure	x_{17}	Misuse
x_4	Too much corner	x_{18}	Illegal operation

B. Hierarchical Bayes Estimation

When the prior distribution of R is uncertain, a more conservative lower bound R_L of R is $0 \le R_L < 1$, and then take $\pi(R), R_L < R < 1$ from $(R_L, 1)$, such as $0.7 \le R_L < 0.9$. If a value is given to R_L, a greater deviation may occur, so we need to give a priori distribution to the parameter R_L, such as the *Beta* distribution commonly used in binomial distribution.

When $0 < b \le 1$, $a > 1$, the Beta function is an increase function; At the same time we find that when $b = 1$, the larger the a is, the smaller the tail of the Beta distribution function is. In this case, the robustness of Bayes estimation is worse [7]. Therefore, the value of *a* should have an upper limit of *c*, that is 1<*a*<*c*. So, $\pi_2(a) = u(1,c), \pi_3(b) = u(0,1)$, c is constant. Then the hierarchical Bayes estimates for *R* is shown as:

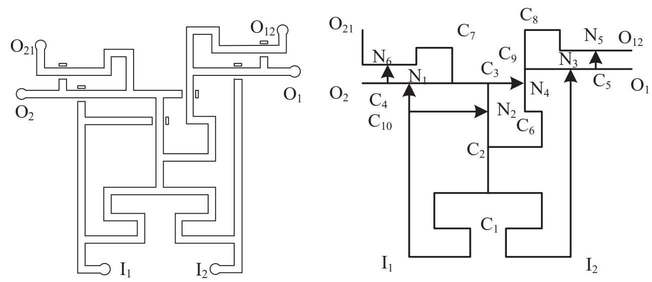
$$\hat{R}_{HB} = \frac{\int_1^c \int_0^1 \left[B(a+n+1,b)/B(a,b)\right] \mathrm{d}a\mathrm{d}b}{\int_1^c \int_0^1 \left[B(a+n,b)/B(a,b)\right] \mathrm{d}a\mathrm{d}b}. \qquad (2)$$

When the confidence level of *R* is *α*, The one-sided lower confidence limit of multilayer Bayes *RH*, *BL* is shown as:

$$1-\alpha = \frac{\int_1^c \int_0^1 \left[B(a+n,b)/B(a,b)\right] I_{R_{BL}}(a+n,b) \mathrm{d}a\mathrm{d}b}{\int_1^c \int_0^1 \left[B(a+n,b)/B(a,b)\right] \mathrm{d}\,a\,\mathrm{d}\,b}. \qquad (3)$$

C. Case Study

Consider an ELN with two-input-four-output as shown in Fig. 3. . N_i represents the serial number of null gate, I_i represents the input port of detonation wave, O_i represents the output port of detonation wave, and C_i represents the symbol of corner. The size of the channel is 1.4mm*1.0mm in the improved gap null gate. The explosive is mainly RDX and the detonation velocity is 7202m/s [8-9].



(a) The Structure of ELN (b) Logic Circuit of ELN

Figure 3. Diagram of An ELN with Two-Input-Four-Output

IV. STORAGE HEALTH ASSESSMENT OF ELN SYSTEMS BASED ON INFORMATION FUSION

In accord with the physical and chemical changes about system state of ELN based on fault tree, we describe the relevant state parameters. Then, we construct the framework of health status evaluation based on test information, history information and environmental data. Finally, D-S evidence theory is used to integrating information for acquiring the health state level of the whole ELN system.

A. D-S Evidence Combination Rule and Evidence Source Correction

Evidence theory is an extremely effective method of uncertainty reasoning. *P(A)* is the probability of focal element *A*, *Bel* and *Pl* are belief and plausibility measures. Let $m_1, m_2, \cdots, m_n$ be the basic probability assignments (BPA) over Θ , Dempster's rule of evidence combination can be expressed as:

$$m(A) = \begin{cases} \dfrac{1}{1-K} \sum\limits_{\cap A_i = A} \prod\limits_{1 \le i \le N} m_i(A_i), & A \ne \varnothing \\ 0 & A = \varnothing \end{cases}, \tag{4}$$

where $K = \sum\limits_{\cap A_i = \varnothing} \prod\limits_{1 \le i \le N} m_i(A_i)$ represents the conflict coefficient. When *K*=0, the evidences are not conflict. When *K* tends towards 1, there is highly conflict for evidence.

While evaluating ELN system and integrating different health state information, the source of the evidence needs to be corrected to obtain the weight assignment values.

Suppose there are *n* evidence sources in the evidence synthesis process, let the weight of the *i* -th evidence source be *wi*, we can modify the original evidence source as follows:

1. Determine the weight vector for each evidence source

$$w = (w_1, w_2, \cdots w_n). \tag{5}$$

2. $w_{\max} = \max(w_1, w_2, \cdots, w_n)$, the relative weight vector is $w^* = (w_1, w_2, \cdots, w_n)/w_{\max}$, Let the BPA coefficient of each evidence source be $\alpha_i = w_i / w_{\max}$, then the revised result of BPA is:

$$m_i^*(A) = \alpha_i m_i(A). \tag{6}$$

3. the corrected BPA of the evidence source should satisfies (4), the sum of all basic probabilities is 1, we can give its inadequacies to the uncertainty

$$m_i^*(U) = 1 - \sum m_i^*(A). \tag{7}$$

B. State Parameters Analysis of ELN

The determination of the health state parameters is the first step in health state evaluation for ELN, as shown in Fig. 4.

1) Test information index

From the failure analysis in the second section, the influence of the external environment factors on ELN is mainly reflected in the detonation performance.

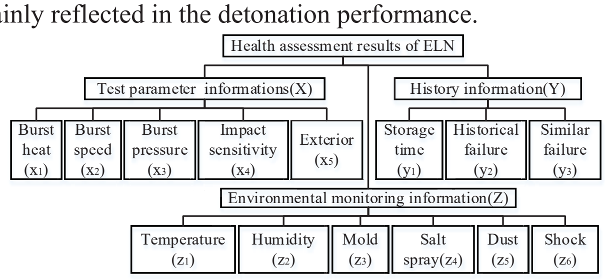


Figure 4. Health State Parameters of ELN System

2) Historical information index

The historical information index mainly characterizes the health information of ELN. It mainly considers the storage information and failure information, the storage index H_t :

$$H_{y_1} = 1 - \frac{T}{T_0}, \tag{8}$$

where *T* is years of storage, T_0 is the system theory of storage life.

The sampling number of sampling test is $N_i(i = 1, 2, \cdots n)$ and the number of failure is f_i, so the failure index H_f is:

$$H_{y_2} = \frac{1}{n} \sum_{i=1}^{n} \frac{f}{N}. \tag{9}$$

The same type of failure information is calculated in the same way as (9), then the comprehensive priori index H_y of ELN is:

$$H_y = \sum_{i=1}^{3} w_{y_i} H_{y_i} , \tag{10}$$

where w_i is the weight of each state parameter.

3) Environmental monitoring index

As shown in Table III , some factors belong to quantification information [10], such as the temperature, humidity, etc. Other factors cannot be quantified, such as the mold, dust, etc. The temperature and humidity requirements for the pyrotechnic library obtained from GJB 78A-2002.

TABLE III. THE TEMPERATURE AND HUMIDITY REQUIREMENT

Temperature ℃			Humidity %		
general	***limit***	***suitable***	***general***	***limit***	***suitable***
<30	-12-30	5-20	<70	40-70	55-65

According to the above table, we can get the temperature index and humidity index:

$$H_{z,j} = \begin{cases} 1, & k \in suitable \\ 0.5 & k \in general \\ 0.1, & k \in \lim it \end{cases}, \tag{11}$$

where *k* is the range of temperature or humidity, *j* represents the corresponding parameters. The value of H_z is shown as:

$$H_z = \sum_{i=1}^{2} w_{z_i} H_{z_i} . \tag{12}$$

C. The Framework of Health State Evaluation for ELN

As a key part of the fuse system, the health state of the explosion logic network during storage will affect the reliability and safety of the whole fuse. Fig. 5 shows that after obtaining the information on the health state of ELN system, it is necessary to solve the parameters that characterize the state of ELN and normalize the quantization. Then we need to solve and normalize the weight of each state parameter, while establishing the triangular fuzzy membership function of the state parameter under the identification framework to obtain the membership degree of the state parameter. Finally the state parameters derived from the three types of information are converged by evidence theory to measure the health level of ELN.

The health level of the ELN is divided into five levels: Good, normal, general, poor, bad. We adopt the extension AHP [11-12] to analyze the weight of each level.

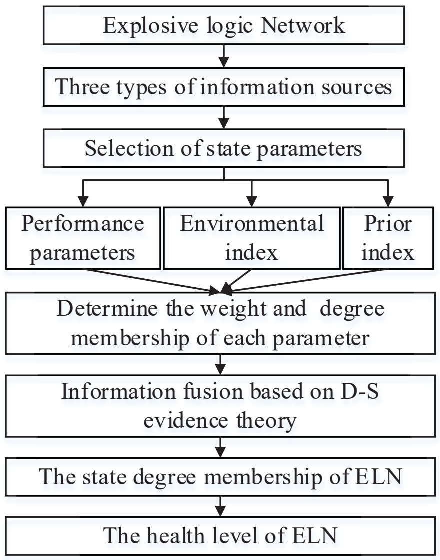


Figure 5. System Evaluation Process

The specific steps of determining the weight of the index by extension analytic hierarchy process are as follows:

1) Establishing an extension judgment matrix

After building the hierarchy structure by comparing one factor with others, an extension judgment matrix A is established to illustrate the factor's impact among them.

$A=\{a_{ij}\}$, $a_{ij}=<a_{ij}^-, a_{ij}^+>$, a_{ij} is an extension interval, A is a reciprocal matrix, it satisfies the following requirements: $1/9\le a_{ij}^- \le a_{ij}^+ \le 9$, $a_{ii}=1$, $a_{ij}=a_{ji}^{-1}$, $i, j=1,2,\cdots,n$.

2) Calculating the comprehensive extension matrix and the weight vector

The number of integrated extension intervals for the k -th layer is shown as:

$$A_{ij}^k = \frac{1}{T} \otimes \left(a_{ij}^1 + a_{ij}^2 + \cdots + a_{ij}^T \right). \tag{13}$$

From (13), the integrated extension interval matrix for the k-th layer is: $A=(A^-, A^+)$. The steps of satisfying the weight vector and the consistency requirement is shown as:

a) Calculate the normalized eigenvector

b) Calculate parameters with A^- and A^+:

$$k = \sqrt{\sum_{j=1}^{n_k} \frac{1}{\sum_{i=1}^{n_k} a_{ij}^+}}, \qquad m = \sqrt{\sum_{j=1}^{n_k} \frac{1}{\sum_{i=1}^{n_k} a_{ij}^-}}. \tag{14}$$

c) Obtain weight vectors as below:

$$S^k = \left(S_1^k, S_2^k, \cdots s_{n_k}^k \right) = (kx^-, mx^+). \tag{15}$$

3) Obtaining hierarchy single order

We can calculate $V(S_i^k \ge S_j^k)$, if $\forall i = 1,2,\cdots n_k$ and $V(S_i^k \ge S_j^k) \ge 0$, then:

$$P_{jh}^k = 1, P_{ih}^k = V\left(S_i^k \ge S_j^k \right) \quad i, j = 1,2,\cdots,n_k; i \ne j, \tag{16}$$

where P_{ih}^k represents a single sort of the i-th indicator on the k-th layer by normalization:

$$P_h^k = \left(p_{1h}^k, p_{2h}^k, \cdots p_{n_k h}^k \right)^T, \tag{17}$$

where $V(a \ge b)$ represents probability of $a \ge b$ and could be calculated below:

$$V(a \ge b) = \frac{2\left(a^+ - b^-\right)}{\left(b^+ - b^-\right) + \left(a^+ - a^-\right)}. \tag{18}$$

When constructing the extension judgment matrix, it is necessary to pay attention to experts as much as possible to cover the multidisciplinary and multi-level because the subjectivity is strong in the extension interval judgment matrix and the analytic hierarchy process.

In the paper, we only need to calculate the historical information index and monitoring information index. Taking the historical information index as an example, six experts are selected to score the weight of the historical information storage time y_1, the historical failure y_2 and the similarity failure y_3, the comprehensive extension interval judgment matrix of historical information indexes are as shown in Table IV.

TABLE IV. COMPREHENSIVE EXTENSION INTERVAL MATRIX

index	y_1	y_2	y_3
y_1	(1,1)	(1.483,1.9833)	(1.2833,1.6834)
y_2	(0.5042,0.6742)	(1,1)	(0.5504,0.7594)
y_3	(0.5940,0.7792)	(1.3167,1.8167)	(1,1)

From Table IV , we can obtain:

$$A^- = \begin{bmatrix} 1 & 1.4833 & 1.2833 \\ 0.5042 & 1 & 0.5504 \\ 0.5940 & 1.3167 & 1 \end{bmatrix},$$

$$A^+ = \begin{bmatrix} 1 & 1.9833 & 1.6833 \\ 0.6742 & 1 & 0.7594 \\ 0.7792 & 1.8167 & 1 \end{bmatrix}.$$

Calculate the normalized feature vector:

$$x^- = [0.441,\ 0.2322,\ 0.3268],\ x^+ = [0.4371, 0.2339, 0.3289].$$

From (11), we can calculate k=0.9085, m=1.0453. then we can obtain:

$$S_1 = (0.4006,\ 0.4569), S_2 = (0.211,\ \ 0.2446), S_3 = (0.2969,\ 0.3438),$$

$$V\left(S_1 \ge S_2\right) = 5.4705, V\left(S_3 \ge S_2\right) = 3.2994.$$

we can calculate value from (11):

$$P_1 = 5.4705, P_2 = 1, P_3 = 3.2994.$$

Therefore, the weight of the three indexes of the historical information is shown as:

$$w_y = \left(0.5599, 0.1024, 0.3377\right).$$

The weight of the state index in the environmental monitoring information can be obtained as the above method.

D. *Case Study*

Take the ELN with Two-Input-Four-Output as an case. The test parameters are shown in the following table.

TABLE V. THE TEST PARAMETERS OF ELN

Parameters	test value	standard value	Error limit
x_1/ MJ·kg^{-1}	5-4	5-6	±1.2
x_2/ mm*μs^{-1}	7.216	7.42	±0.50
x_3/ Gpa	20.2	22.6	±5.0
x_4/ %	58.2	54	±13.0
x_5	Not rusty	Not rusty	-

Three types of state information can be shown as Table VI :

TABLE VI. STATE INDEXES OF VARIOUS INFORMATION

H_i	H_x	H_y	H_z
State parameters	0.9111	0.8265	1.0

Using (13) – (15), we can get the membership degree and weight of ELN state parameters, as shown in Table VII:

TABLE VII. MEMBERSHIP DEGREE OF STATE PARAMETERS

	good	normal	general	poor	bad	weight
H_x	0.5555	0.4445	0	0	0	0.4944
H_y	0.1325	0.8675	0	0	0	0.3227
H_z	1	0	0	0	0	0.1829

We find that the test parameter index weight coefficient is the largest one, that is

$$w_{max} = 0.4944 .$$

So we can calculate the conversion factors value of three state parameters: 1, 0.6527 and 0.3699.

According to the evidence combination rule in (4), the three evidence sources are synthesized, and the parameters H_x and H_y are synthesized first.

$$K_1 = m_{H_x}(\theta_1)m_{H_y}(\theta_2) + m_{H_x}(\theta_2)m_{H_y}(\theta_1) = 0.353 ,$$

$$m_1(\theta_1) = \frac{m_{H_x}(\theta_1)m_{H_y}(\theta_1) + m_{H_x}(\theta_1)m_{H_y}(\theta)}{1-K_1} = 0.3725 ,$$

$$m_1(\theta_2) = 0.6275 .$$

The three parameters can be synthesized, then the results can be obtained:

$$\beta = (0.4851, 0.5149, 0, 0, 0\ ) .$$

The value of β indicates that the health level of ELN with Two-Input-Four-Output is normal.

V. CONCLUSIONS

This paper is devoted to find the resolution of functional reliability evaluation of ELN systems and health status assessment issues, using detonation wave propagation theory of condensed explosives, and multi-source information fusion method as research tools. The paper counts and analyses the test data of explosive gap null gate and establishes the mathematical model of the function reliability of explosive logic null gate, carrying out the research on the functional reliability of ELN system and explosive gap null gate.

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