Time-change Reliability Assessment and Analysis of Cryogenic Pneumatic Valve Based on Dynamic Bayesian Network Theory

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Abstract. In order to fully identify the root cause of cryogenic pneumatic valve failure in the process of liquid rocket engine test, and to analyze the dynamic time change of the process of cryogenic pneumatic valve reliability analysis, this paper first analyzes the failure factors of low temperature pneumatic valve in the test process of liquid rocket engine according to the human-machine environment system engineering. By introducing the dynamic Bayesian network theory, and by means of analyzing the time-change failure failure mode of cryogenic pneumatic valve, constructing the time-change reliability model of cryogenic pneumatic valve was constructed in the test process of liquid rocket engine, and the reliability growth technology of cryogenic pneumatic valve was researched by the optimal failure search strategy. Finally, the validity and accuracy of this method are verified by the example. This method can provide a method guide for quantitative analysis and improvement of the reliability of cryogenic pneumatic valve, and provide support for the accurate and objective evaluation and development of liquid rocket engine performance.

Keywords: Dynamic Bayesian network; Cryogenic pneumatic valves; Reliability.

1. Introduction

Reliability of cryogenic pneumatic valve during the test process of rocket engine not only affects the reliability and safety of the test system, but also affects the evaluation of engine performance parameters during the test process, and even affects the engine damage, casualties and economic losses of the test process. Because the load, operating condition, stress and other operating environment and parameters of the rocket engine test process are dynamic and time-varying, the rocket engine test process is a complex dynamic process[1-2]. Due to the dynamic characteristics of the rocket engine test process, the flow, pressure and impact of the cryogenic pneumatic valve are time-varying parameters, so that cryogenic pneumatic valve has dynamic characteristics in the test process. Therefore, it will be difficult to obtain accurate failure data and reliability information of cryogenic pneumatic valve without considering the dynamic characteristics of cryogenic pneumatic valves. In addition, the characteristic of most cryogenic pneumatic valves change gradually with time, such as, fatigue, wear, corrosion[3-4]. By the reduction of mechanical strength, so that the performance parameters of cryogenic pneumatic valve gradually change over time, and reliability shows the characteristics of time changes.

Therefore, the research on the reliability of cryogenic pneumatic valve need change from static reliability to time-changing reliability. By studying the reliability of cryogenic pneumatic valve, the optimal design and safe operation of cryogenic pneumatic valves will be promoted. However, because the problem of dynamic reliability is much more complex than the static reliability problem, with the complexity of product function and structure and the improvement of people’s product reliability
requirements, the theory of dynamic reliability modeling has been highly concerned, and the research of
dynamic reliability has become a hot research topic at home and abroad in recent years.

2. Human-machine-environmental Impact Factors for the Reliability of Cryogenic Pneumatic Valve

The influencing factors of cryogenic pneumatic valve reliability are various including various
parameters related to the rocket engine test process such as material characteristics (e.g. stem material
selection, fastener material selection, valve body/valve cover/valve seat/opening and closing parts),
structural design parameters (e.g. long neck valve cover structure, valve body structure, pressure relief
component structure, upper sealing device structure), low temperature valve inspection (e.g. shell
hydraulic strength test, hydraulic pressure/air pressure seal test, upper seal test, and opening and torque
test), operating media performance (e.g. media temperature, pressure, flow, density, dew point, leakage),
human factors (e.g. installation error, rotational inertial force, rotation time), environmental factors (e.g.
ambient temperature, vibration, low temperature compensation). Therefore, it is necessary to determine
the key factors from the complex various factors, so as to avoid the safety hazards of cryogenic
pneumatic valve from the root cause and ensure its operational stability.

The human-machine-environment system engineering is established by Qian Xuesen, to reveal the law
of the relationship between man, machine and environment by applying the thoughts and methods of
system engineering. Compared to the human-machine systems engineering and 5M1E (Man, Machine,
Material, Method, Measure, Environment) field quality control methods, human-machine-
environmental systems engineering not only analyzes the individual performance of the components,
and also coupling connections among components[5]. The factors influencing the reliability of
cryogenic pneumatic valve can be expressed as:

\[
Q = (PW \cup PM \cup PE) \\
= \{p_{s1}, p_{s2}, \ldots, p_{sk}\} \cup \{p_{m1}, p_{m2}, \ldots, p_{mk}\} \cup \{p_{e1}, p_{e2}, \ldots, p_{ek}\}
\]

In the formula, \(PW\) is the human influencing aspects of cryogenic pneumatic valve reliability in the test
process of liquid rocket engine; \(PM\) is the human influencing aspects of cryogenic pneumatic valve
reliability in the test process of liquid rocket engine; \(PE\) is the human influencing aspects of cryogenic
pneumatic valve reliability in the test process of liquid rocket engine; \(p_{si}\) is human-machine
environmental impact event of cryogenic pneumatic valve reliability in the test process of liquid rocket
engine, such as rotation inertial force, rotation time, etc; \(px_i\) is the human-machine-environment
influencing factor of cryogenic pneumatic valve reliability in the test process of liquid rocket engine.

3. Time-change reliability Model of Cryogenic Pneumatic Valve Based on Dynamic Bayesian
Network

3.1. Dynamic Bayesian network constructing

Due to the many factors affecting the time-varying reliability of cryogenic pneumatic valve in the test
process of liquid rocket engine, the correlation is complex, and reliability is greatly influenced by
external environmental influences[6]. Reliability will be changed quickly and sometimes several adverse factors appear at the same time. All these bring great difficulties to the accurately calculation of the time-change reliability of cryogenic pneumatic valve in the test process of liquid rocket engine[7-8].
In addition, the rocket engine test process also need to make diagnostic reasoning in sometimes, and
need to determine the source of failure, so that the test process need to develop improvement measures.
By the introducing of dynamic Bayesian network, time-change reliability assessment model of
cryogenic pneumatic valve based on dynamic Bayesian network theory is established. Dynamic Bayesian network is a modeling and reasoning method for dynamic systems in recent years. It adds
time factor on the basis of static Bayesian network, which makes the process of event reasoning more consistent and more time-change characteristics. At the same time, the probability method is used to
describe with expert knowledge, combined with historical information and evidence library, with
information time accumulation ability, and it can more effectively reduce the uncertainty in the process
of information fusion reasoning at different levels, and can meet the requirements of time-change reliability. By means of in the cryogenic pneumatic valve failure tree during the rocket engine test process, Dynamic Bayesian network can describe the polymorphism of the event, can be regarded as a special case of the node in Bayesian network[9-10].

The logic gate in the failure tree describes the logical relationship among parent-child events, and its structural function can be expressed as a conditional probability. The logical relationship among parent-child events can be expressed as:

$$\begin{align*}
FTA \rightarrow DBN & \begin{cases}
(C_1,\ldots,C_n) \rightarrow (N_1,\ldots,N_n) \\
(F,T) \rightarrow (S_1,S_2,\ldots,S_n) \\
(SF) \rightarrow (CP)
\end{cases}
\end{align*}$$

(2)

In the formula, \(C_1,\ldots,C_n\) are events in failure tree mode; \(N_1,\ldots,N_n\) are the special case of nodes in Bayesian network; \(F,T\) are the failure state and normal state analyzed by the failure tree mode; \(S_1,S_2,\ldots,S_n\) are the polymorphism of the dynamic Bayesian network; \(SF\) are the structural function of the failure tree mode; \(CP\) are the conditional probability of the dynamic Bayesian network.

The failure tree of cryogenic pneumatic valve is converted to conversion relationship table as shown in TABLE I.

**Table 1.** Conversion relationship table.

| AND gate | Disjunction gate | 2/3 vote gate |
|----------|------------------|--------------|
| Failure tree |
| | B | C |
| Dynamic Bayesian network |
| | B | C |
| Condition probability |
| \(P(A=1|B=0,C=0)=0\) | \(P(A=1|B=0,C=0)=0\) | \(P(A=1|B=0,C=0)=0\) |
| \(P(A=1|B=1,C=0)=1\) | \(P(A=1|B=1,C=0)=1\) | \(P(A=1|B=1,C=0)=1\) |
| \(P(A=1|B=0,C=1)=0\) | \(P(A=1|B=0,C=1)=0\) | \(P(A=1|B=0,C=1)=0\) |
| \(P(A=1|B=1,C=1)=1\) | \(P(A=1|B=1,C=1)=1\) | \(P(A=1|B=1,C=1)=1\) |
| \(P(A=1|B=0,C=0)=0\) | \(P(A=1|B=0,C=0)=0\) | \(P(A=1|B=0,C=0)=0\) |
| \(P(A=1|B=1,C=0)=1\) | \(P(A=1|B=1,C=0)=1\) | \(P(A=1|B=1,C=0)=1\) |
| \(P(A=1|B=0,C=1)=0\) | \(P(A=1|B=0,C=1)=0\) | \(P(A=1|B=0,C=1)=0\) |
| \(P(A=1|B=1,C=1)=1\) | \(P(A=1|B=1,C=1)=1\) | \(P(A=1|B=1,C=1)=1\) |

3.2. Time-change reliability model of a cryogenic pneumatic valve

A time-change reliability model of a cryogenic pneumatic valve based on a dynamic Bayesian network is constructed, and the conversion process is shown in FIGURE I.
In Figure 1, $S$ is the result of the failure of the cryogenic pneumatic valve, the number of failure symptoms $P_i (1 \leq i \leq n)$ is caused by human factors. The reliability assessment and analysis of cryogenic pneumatic valves is expressed as:

$$P(S) = \sum_{j} [P(S|F)P(F)] = \sum_{j} [P(S|F)P(F) \cdot \prod_{i=1}^{n} P(F_i)]$$

(3)

According to Bayesian network theory [6,7], there is:

$$P(F|E) = \frac{P(E|F)P(F)}{P(E)} = \frac{P(E|F) \cdot \prod_{i=1}^{n} P(F_i)}{\sum_{j} [P(E|F) \cdot \prod_{i=1}^{n} P(F_i)]}$$

(4)

There is:

$$P(F_i|E) = 1 - \sum_{j \neq i} P(F_i|E)$$

(5)

In Bayesian network, $R$ is the set of paths from the failure result node to the cause node, $R = (R_1, R_2, \ldots, R_m)$. $M_K$ is the path of the middle transition node from the result node to the cause node[11].

4. Example

Based on the hydraulic oxygen low-temperature pneumatic valve of a liquid oxygen engine test bench, the reliability of time change is analyzed based on the human-machine environmental system engineering to ensure the stable and reliable operation of the low-temperature valve. Analysis of the environmental impact factors of a low-temperature pneumatic valve.

Through preliminary analysis, the reliability of low-temperature pneumatic valves is analyzed by the main factors common to cryogenic pneumatic valves. The main factors common to cryogenic pneumatic valves include: human aspects (inspection cycle, operating condition, operating status, 3
personnel influencing factors), machine aspects (operating gas pressure, stem status, stem material, seal, processing accuracy, assembly status, spring performance, 6 machine influencing factors), environmental aspects (environmental vibration, Media temperature, media flow, media pressure, 4 environmental impact factors), a total of 13 personal aircraft environmental impact factors.

Reliability analysis of a cryogenic pneumatic valve the reliability and loss efficiency of the human-machine environmental factors of cryogenic pneumatic valve are shown in TABLE II.

Table 2. Reliability and loss of efficiency of environmental impact factors of a cryogenic pneumatic valve man-machine.

| Influencers factors Pij | Reliability K_i(t) | Loss of efficiency \(\lambda_i(t)\) | Influencers factors Pij | Reliability K_i(t) | Loss of efficiency \(\lambda_i(t)\) |
|-------------------------|---------------------|-----------------|-------------------------|---------------------|-----------------|
| Check cycle             | 99.99%              | 1/10^6h         | Operating gas pressure  | 99.99%              | 1/10^6h         |
| Operation specification | 99.99%              | 1/10^6h         | working accuracy        | 99.99%              | 1/10^6h         |
| operating status        | 99.99%              | 1/10^6h         | spring performance      | 98.65%              | 1/10^6h         |
| Stem state              | 99.99%              | 1/10^6h         | temperature             | 99.99%              | 1/10^6h         |
| Assembly state          | 99.99%              | 1/10^6h         | Dielectric flow rate    | 99.99%              | 1/10^6h         |
| environment vibration   | 99.99%              | 1/10^6h         | Dielectric pressure     | 99.99%              | 1/10^6h         |

The failure rate of this cryogenic pneumatic valve is:

\[ \lambda = \sum_{i=1}^{n} \lambda_i(t) = 27/10^5h \]

By means of TABLE II, it can be seen that the time-variable reliability of the cryogenic pneumatic valve is 96.71%, the failure rate is 27/10^5h. According to the time-varying reliability model of the cryogenic pneumatic valve based on the dynamic Bayesian network, there are nine dependency paths between nodes in Bayesian network, among which:

\[ R_g = \max \{P(F_1 | M, e)\} = \{K_1(t), K_2(t), K_3(t), K_4(t), K_8(t), K_{11}(t), K_{12}(t), K_{13}(t)\}, \]

\[ K_{11}(t), K_{12}(t), K_{13}(t) = 0.0326 \]

That is, the strongest path is operating state, environmental vibration, seal, operating air pressure, spring performance, media temperature, media flow, media pressure. For the most reliable path of cryogenic pneumatic valve, the reliability distribution and loss efficiency distribution of the main factors are shown in FIGURE II and FIGURE III.

Figure 2. Reliability distribution of a cryogenic pneumatic valve.
By FIGURE II and FIGURE III, sealing ring performance and spring performance are not only located in the strongest reliability path of cryogenic pneumatic valve reliability, but also have the lowest reliability and maximum loss efficiency, so that seal ring performance and spring performance become the most likely cause of cryogenic pneumatic valve failure. According to the actual use, due to seal failure and spring performance may lead to cryogenic pneumatic valve leakage and shutdown time, etc., easy to cause cryogenic pneumatic valve anomalous. In order to improve the time-change reliability of the cryogenic pneumatic valve, and improve the reliability of the cryogenic pneumatic valve, the weak links such as sealing ring performance and spring performance can enhance the reliability of the cryogenic pneumatic valve.

5. Conclusions
In this paper, a time-variable reliability model of cryogenic pneumatic valve in the test process of liquid rocket engine was constructed. The reliability improving technology of cryogenic pneumatic valve was studied based on an optimal strategy. Finally, the quantitative analysis and improvement reliability of cryogenic pneumatic valve were realized, so that the maintenance cost of cryogenic pneumatic valve was reduced, and the stability of the liquid rocket engine test process was improved.

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