The Reliability Estimation for the Open Function of Cabin Door Affected by the Imprecise Judgment Corresponding to Distribution Hypothesis

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Abstract. With the development of artificial intelligence, more and more reliability experts have noticed the roles of subjective information in the reliability design of complex system. Therefore, based on the certain numbers of experiment data and expert judgments, we have divided the reliability estimation based on distribution hypothesis into cognition process and reliability calculation. Consequently, for an illustration of this modification, we have taken the information fusion based on intuitional fuzzy belief functions as the diagnosis model of cognition process, and finished the reliability estimation for the open function of cabin door affected by the imprecise judgment corresponding to distribution hypothesis.

1. Introduction

In the reliability design of cabin door system, complicated working condition and expensive experiment cost have made experts to complete reliability estimations under the limited experiment data. Therefore, when the reliability estimation can be separated into the cognition process of distribution hypothesis and reliability calculation based on distribution hypothesis, the reliability estimation relied on expert judgments (e.g., “It seems to obey Welbul distribution.”, ”It seems to obey exponential distribution.”) have become an meaningful research for reliability design of engineering system.

For this kind of reliability estimation, some experts have separated expert judgments from other reliability data and put them in the group of informative prior for the reliability estimations under the Bayesian framework. For example, Rajabi etc. have has used approximate posterior distribution derived from surrogate modeling for an approach of accelerating the fuzzy Bayesian inference algorithm[1]. As the uncertainties of expert judgments, Coolean has also discussed the use of imprecise probability in reliability estimation, which have translated expert judgment into imprecise probability under Bayesian framework[2]. Moreover, Cizelj etc. have proposed a likelihood function for the Bayesian inference, which has aggregated the influence from component operating conditions on component failure rate[3].

However, as subjective judgments can be easily affected by environment factors and personal preference, rational judgment based on information fusion seems to be more convincible than
intuitional judgment based on personal preference [4–7]. Therefore, besides the quantification of single judgments, experts have also proposed subjective quantification methods based on D-S theory[8–12], Bayesian-belief net[13–15] or neuronal network[16]. Moreover, when Intuitionistic Fuzzy (IF) set is regarded as a better quantification method than fuzzy set for the subjective quantification, the information fusion based on IF sets has also attracted the experts’ attention[17,18]. Consequently, different from the reliability estimation under Bayesian framework, some reliability experts have highlighted the importance of expert judgments and used Human Reliability Analysis (HRA) for the reliability estimation relied on expert judgments, which has aggregated cognition process in the calculation[19–21]. Owing this, three generations of HRA methods can be sorted by the performance shaping factor(PSF), static cognition process and dynamic cognition process[22]. Moreover, with the more engineering applications of HRA, experts have proposed more efficient cognition processes for HRA. In the reliability design of nuclear power plant disturbance, Py has proposed a dynamic cognitive method for HRA under the decision dimension, which have separated the cognition process of distribution hypothesis into nine different cognition stages[23], Mkrtchyan etc. have discussed the feasibility of Bayesian belief networks in the HRA, which can aggregate the subjective information and some other types of information[24]. Therefore, to highlight the importance of expert judgments and complete the reliability estimation for the open function of cabin door, here we introduce the cognition process advised in SHARP approach in this reliability estimation process, and separate the reliability estimation into three parts: (1) Observation; (2) Diagnosis; (3) Manual actions[22]. Meanwhile, we have taken IF belief functions proposed by Song as reasoning model in the diagnosis stage, which can complete the information fusion of multiple judgments based on the IF set and D-S theory[25]. Consequently, the first part of this paper is the introductions of IF set theory and information fusion based on IF belief function. Then, the second part is used to introduce the reliability estimation for the open function of cabin door. At last, the discussion and conclusion are used to end this paper.

2. IF set
As a generation of fuzzy set theory, IF set theory proposed by Atanassov can express the hesitation within subjective judgment[26,27]. The main definitions of IF set theory can be expresses as follows:

**Definition 1.** Let $X = \{x_1, x_2, \cdots x_n\}$ be a finite universal set, the IF set is

$$A = \{< x_i, \mu_A(x_i), \nu_A(x_i) > | x_i \in X \},$$

where the functions $\mu_A : X \mapsto [0,1]$ and $\nu_A : X \mapsto [0,1]$ are membership degree and non-membership degree of element $x_i$, respectively [28].

For each $x_i \in X$, if $0 \leq \mu_A(x_i) + \nu_A(x_i) \leq 1$, let $\pi_A(x_i) = 1 - \mu_A(x_i) - \nu_A(x_i)$. $\pi_A(x_i)$ is the third member of IF set $A$, and called the intuitionistic index. Therefore, the simple form of IF set $A$ can be written as $A = \langle \mu_A(x_i), \nu_A(x_i) \rangle$.

3. The information fusion based on IF evidence functions
As a probability estimation method based on the IF set and D-S theory, Song’s method can complete the information fusion of multiple imprecise judgments[25]. The core definitions of this method can be expressed as two parts:

3.1. The probability estimation

**Definition 2.** Let $X = \{x_1, x_2, \cdots x_n\}$ be a universe of discourse, and IF be the family of all fuzzy set correspondence with $X$. Then, the IF belief function of $A_j$ is defined as

$$\{< A_j, m(A_j), \mu_{A_j}(x_j), \nu_{A_j}(x_j) > \},$$

where $A_j$ is an IF event within IF, $\mu_{A_j}(x_j)$ is the membership function of the IF set $A_j$, $\nu_{A_j}(x_j)$ is the non-membership function, $m(A_j)$ is the basic probability assignments (BPA) of $A_j$, and $j = 1,2,\cdots,n$. 
Definition 3. Define the probability estimation based on the different pieces of linguistic information as follows:

\[ P(x_j) = [a_j, b_j], \]

where

\[
\begin{align*}
    a_j &= \sum_{A \in \mathcal{E}} \sum_{i=1}^{n} m(A_i) \mu_A(x_j), \\
    b_j &= \sum_{A \in \mathcal{E}} \sum_{i=1}^{n} m(A_i)(1 - \nu_A(x_j)) + \pi_A(x_j),
\end{align*}
\]

(4)

3.2. The priority based on the probability estimations

Definition 6. Define the \( e_j \) as the priority value of \( P(x_j) \) as

\[ e_j = (a_j + b_j) / 2, \]

(6)

Therefore, for the judgment \( P(x_{\tau_1}) \) and \( P(x_{\tau_2}) \), if \( e_{\tau_1} \geq e_{\tau_2}, P(x_{\tau_1}) \) is better than \( P(x_{\tau_2}) \), where \( \tau_1, \tau_2 \in [1, 2, \ldots, N] \) and \( \tau_1 \neq \tau_2 \).

4. The reliability estimation for the open function of cabin door system

In this paper, the cabin door system contains control system, hydraulic system and a high attitude environment. Since the reliability experiment for the open function in the high attitude environment is difficult to simulate with virtual prototype, here we choose the five parameters as the subsystem of the open function, and the reliability estimation for open function of cabin door system can be expressed as follows:

\[ R_s = R_{P_1} \times R_{P_2} \times R_{P_3} \times R_{P_4} \times R_{P_5} \]

(7)

where \( R_s \) is the usage reliability of open function. \( R_{P_1}, R_{P_2}, R_{P_3}, R_{P_4}, R_{P_5} \) correspond to the usage reliability estimations of the viscosity coefficient of hydraulic fluid \( P_1 \), the noise of control signal \( P_2 \), the synchronous rate of actuator cylinder \( P_3 \), the turbulence environment \( P_4 \), and the gust environment \( P_5 \), respectively.

Meanwhile, to simple the calculation, define \( R_{P_i} \) as the usage reliability based on the unknown distribution hypotheses, and list the rest of subsystem reliability information in Table 1.

| Table 1. Design information |
|-----------------------------|
| Parameter                  | Reliability information                     |
| The viscosity coefficient of hydraulic fluid | Unknown distribution hypothesis |
| The noise of control signal | \( R_{P_2} \sim \text{Weibul}(1, 1.1) \)        |
| The synchronous rate of actuator cylinder | \( R_{P_3} \sim \text{Weibul}(1, 1.2) \)        |
| Random turbulence          | \( R_{P_4} = [0.9, 0.95] \)                  |
| Random time of gust         | \( R_{P_5} = [0.9, 0.95] \)                  |
Therefore, based on these background, the reliability estimation for the open function of cabin door system can be expressed as

\[ R_5 = R_{P_1} \times R_{P_2} \times R_{P_3} \times R_{P_4} \times R_{P_5}, \]  

(8)

where

\[
\begin{align*}
R_{P_1} &= \bar{R}_{P_1} \times P_1 \\
R_{P_2} &= 1.1x^{1.1}e^{-x^{1.1}} \\
R_{P_3} &= 1.2x^{0.2}e^{-x^{0.2}} \\
R_{P_4} &= \bar{R}_{P_4} = [0.9, 0.95]
\end{align*}
\]

(9)

\( \bar{R}_{P_i} \) is the reliability estimation based on the distribution hypothesis, and \( P_i \) is the probability estimation for the expert judgment corresponding to the hypothesis distribution.

Moreover, based on the cognition process advised in SHARP approach[22], the flow chart of this reliability estimation can be expressed as follows:

**Figure 1.** Flow chart of reliability estimation

4.1. *Information collection*

In figure 2, expert needs to find the most appropriate Pareto distribution hypotheses for \( P_i \), where has presented the five experiment data and fitting results with the time interval (30 days) as abscissa and the reliability estimation the corresponding absorbency.

4.2. *The quantification for the basic subjective judgment*

Based on figure 2 and expert experience, the subjective information corresponding to each distribution hypothesis has been calculated with equation 3, which have been aggregated in table 2.

4.3. *The probability estimation based on IF belief functions*

With equations (3-6), the probability estimation and priority value of distribution hypothesis can be calculated in table 3. As the priority value of Weibul (1,1) is the biggest, the distribution hypothesis of \( P_i \) can be regarded as Weibul (1,1), and the probability estimation of expert judgments is \([0.34, 0.41]\).

4.4. *The reliability estimation at \( x = 0.4 \)*

With the cognition process above, it is easy to calculate the usage reliability of open function. Therefore, when usage time \( x = 0.4 \), the reliability estimation can be calculated as
\[ R_3 = [a', b'] \times \bar{R}_{\eta} \times 1.32x^{0.3}e^{-e^{-x1.12}} \times R'_\eta \times R_\eta = 1.32 \times [a', b'] \bar{R}_{\eta} \times x^{0.3}e^{-e^{-x1.12}} \times R'_\eta \times R_\eta, \quad (10) \]

where
\[
\begin{bmatrix}
[a', b'] = [0.34, 0.41] \\
R'_\eta = R_\eta = [0.9, 0.95]
\end{bmatrix}
\]  

Consequently, the usage reliability of open function at \( x = 0.4 \) is \( R_x = [0.0162, 0.049] \).

### Table 2. The expert information

| Expert judgment   | BPA        | Frame of discernment | Expert preference | Expert judgment in the form of IF set |
|-------------------|------------|----------------------|-------------------|--------------------------------------|
| It may be         |            |                      |                   |                                      |
| Weibul(1,1) or Weibul(0.9,0.7). | \( m_1 = 0.6 \) | Weibul (1, 1)        | 0.75              | [0.80, 0.10]                         |
|                   |            | Gamma (0.642,0.333)  | 0.35              | [0.40, 0.50]                         |
|                   |            | Weibul (0.9, 0.7)    | 0.65              | [0.70, 0.20]                         |
| It may be         |            |                      |                   |                                      |
| Weibul(0.9,0.7).  | \( m_2 = 0.3 \) | Weibul (1, 1)        | 0.85              | [0.90, 0]                            |
|                   |            | Gamma (0.642,0.333)  | 0.35              | [0.40, 0.50]                         |
|                   |            | Weibul (0.9, 0.7)    | 0.75              | [0.80, 0.10]                         |
| It may be         |            |                      |                   |                                      |
| Gamma(0.642,0.333). | \( m_3 = 0.1 \) | Weibul (1, 1)        | 0.25              | [0.30, 0.60]                         |
|                   |            | Gamma (0.642,0.333)  | 0.45              | [0.50, 0.40]                         |
|                   |            | Weibul (0.9, 0.7)    | 0.55              | [0.60, 0.30]                         |

### Table 3. The probability estimations

| Index            | The probability estimation of expert judgment | The priority value |
|------------------|---------------------------------------------|--------------------|
| Weibul(0.9,0.7)  | [0.34,0.41]                                  | 0.375              |
| Gamma(0.642,0.333) | [0.20,0.26]                                | 0.23               |
| Weibul(1,1)      | [0.4,0.56]                                   | 0.48               |

5. Discussion

5.1. The feasibility

In figure 3, two reliabilities of the viscosity coefficient of hydraulic fluid have been used as a comparison. The reliability ignored the influence from expert judgments have supplied an acceptable estimation result at \( x = 0.4 \), and the reliability under IF belief function and IF set has supplied a dangerous estimation result. As the core of this calculation is just a prediction based on the limited experiment data, a dangerous estimation result seems to be convincible and acceptable. Therefore, to emphasize the influence from expert judgment to reliability estimation, this modification can be regarded as feasible.

5.2. The limitation

As the flow chart has described, although the dynamic cognition process may be more appropriate for the human cognition process, we have used the static cognition process to simulate the cognition process in the reliability estimation. This is because the limit experiment data may cause not only the uncertainties if fitting results but also the short of expert experience. Therefore, this static cognition process is more realistic than the dynamic cognition process for the reliability estimation under the limited experiment data.
6. Conclusion
This paper has completed the reliability estimation for the open function of cabin door system, which is affected by the imprecise judgment corresponding to distribution hypothesis. As this reliability estimation is based on the joint probability of expert judgment and traditional reliability, it is not only a reliability estimation for an engineering design but also a meaningful application of HRA, which is meaningful for the engineering design with limited data and less intelligent cognition process.

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