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Environmental stress level evaluation approach based on physical model and interval grey association degree

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Abstract Associating environmental stresses (ESs) with built-in test (BIT) output is an important means to help diagnose intermittent faults (IFs). Aiming at low efficiency in association of traditional time stress measurement device (TSMD), an association model is built. Thereafter, a novel approach is given to evaluate the integrated environmental stress (IES) level. Firstly, the selection principle and approach of main environmental stresses (MESs) and key characteristic parameters (KCPs) are presented based on fault mode, mechanism, and ESs analysis (FMMEA). Secondly, reference stress events (RSEs) are constructed by dividing IES into three stress levels according to its impact on faults; and then the association model between integrated environmental stress event (IESE) and BIT output is built. Thirdly, an interval grey association approach to evaluate IES level is proposed due to the interval number of IES value. Consequently, the association output can be obtained as well. Finally, a case study is presented to demonstrate the proposed approach. Results show the proposed model and approach are effective and feasible. This approach can be used to guide ESs measure, record, and association. It is well suited for on-line assistant diagnosis of faults, especially IFs.

1. Introduction

High rates of false alarms (FAs), cannot duplications (CNDs), and retest OKs (RTOKs) in aircraft avionics have negatively impacted maintenance costs and mission readiness. Studies show that intermittent faults (IFs) are the major causes of many of the problems mentioned above.[1–5] IFs are defined as failures that can automatically recover once they have occurred. They may be activated or deactivated by some external disturbance, such as high G loading, vibration, thermal extremes, or some combinations of stress. Therefore, if the disturbance ends, then the failure would disappear. While permanent faults (PFs), once they appear, do not disappear. A number of environmental stress sources have been identified that can contribute to failures of electronic equipment. When a fault occurs, associating environmental stresses (ESs) with built-in test (BIT) output for enhanced failure analysis can help identify and interpret faults which are environmentally sensitive, especially IFs.[6–9]

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The relationship between accumulated stress and fault modes of equipment has long been recognized.[9] Because of technical limitations, it was until in the early 1980's that a device to measure and record ESs, logistic history, and other information was developed at Battelle Institute, which was limited to place a discrete transducer at a point of interest. It was unable to capture the effect of actual stress history which it exposed to and caused it to fail.[6,9] The emergence of microprocessors and non-volatile memory made time stress measurement device (TSMD) possible. The original TSMD effort started in 1986 at Rome Air Development Center (RADC, now Rome Laboratory, i.e., RL) and a TSMD of $6 \times 3 \times 11/4$ inches and with a weight of about three pounds was developed to fly originally in electronic bays on A-7 and A-10 aircraft. From then on, the topic of TSMD has attracted many scholars and institutions. Microminiaturize TSMD development started in 1987 with a proposal by RL to an AFSC office at Andrews AFB. The micro-TSMD had shock recorder, vibration sensor, DC voltage, temperature measurement, and transient detection. Data reduction techniques were adapted to reduce redundant information and data amount. However, it increased system complexity and caused some important information loss.[6] Because of the limitations of memory space and processor power of micro-TSMD, it is unrealistic and unnecessary to record all of the sensor data. The question of what stress should be collected and stored for future use has been gradually recognized.[1,8,10] Time stress measurement module (TSMM) in aircraft systems developed by Unisys Corporation was only designed to measure temperature, vibration, and shock data.[8] Grumman Aerospace and Electronics Group selected vibration and temperature for environmental testing. As a result, no faults were induced by temperature.[1] Micro-TSMD developed by EADS CCR was used to monitor humidity and temperature of internal atmosphere of a protected case (IP65).[10] In 2008, an intermittent fault detection and isolation system (IFDIS) was developed by Universal Synaptics Corporation. It has unparalleled intermittent fault detection capability combined with an environmental chamber which provides a close match to the thermal and vibration environment in which the unit under test (UUT) experiences during actual flight operations.[5] However, why to select these ESs and their selection principles and procedures were not clear. Another important problem is how to correlate these stress data against faults that have already occurred, namely, how to evaluate and associate these stresses. Unfortunately, to the best of our knowledge, little information has focused on it.

To address the problems mentioned above, this paper mainly studies the selection approach of main environmental stresses (MESs) and key characteristic parameters (KCPs), and the level evaluation approach of integrated environmental stress (IES). The remainder is arranged as follows. In Section 2, a selection approach of MESs and KCPs based on fault mode, mechanism, and ESs analysis (FMMEA) is presented. In Section 3, reference stress events (RSEs) are constructed according to the impact of IES on faults and an association model between integrated environmental stress event (IESE) and BIT output is built. In Section 4, a novel stress level evaluation approach based on interval grey association degree is described and analyzed in detail. A case study and analysis is provided in Section 5. Overall conclusions are drawn in Section 6.

2. Main environmental stresses and key characteristic parameters selection

The ES sources include thermal cycling, humidity, vibration, shock, and so on. These stresses do not always exhibit themselves as simple, discrete, measurable events, but instead the cumulative effect of many events over a period of time.[9] Considering equipment character, environmental profile, associated complexity, and so on, it is unnecessary to measure and record all ESs.[1,8,10] Only MESs should be selected. Let Σ_{MESs} denote the set of MESs. Σ_{MESs} is assumed to be composed of some MESs ES_i, $\Sigma_{\text{MESs}} = \{\text{ES}_1, \text{ES}_2, \cdots, \text{ES}_n\}$.

Each ES has multiple characteristic parameters. For example, the temperature stress includes the average temperature, the highest and lowest temperatures and their lasting times, the maximum change rate of the temperature, and so on. Moreover, each characteristic parameter has different contributions to faults. Taking all characteristic parameters into account would influence the extraction and association of important stress information. Therefore, selecting KCPs of MESs can not only reduce the data amount but also improve the association efficiency. Let Σ_{KCPs} denote the set of KCPs. Σ_{KCPs} is assumed to be composed of some KCPs p_i, $\Sigma_{\text{KCPs}} = \{p_1, p_2, \cdots, p_n\}$.

The relation between ESs and fault modes is the foundation for MESs and KCPs selection. The fault mode effect analysis (FMEA), which is widely applied in the field of reliability, is used for fault mode and effect analysis. The fault mechanism, especially the ESs-fault mechanism, cannot be analyzed with the FMEA. To address this problem, FMEA is extended to FMMEA which is based on the FMEA and ESs-fault mechanism. The flow chart of MESs and KCPs selection is shown in Fig. 1.

The key of FMMEA is figuring out each fault cause and mechanism, especially the mechanism of the faults resulted from ESs. Firstly, the equipment structure is divided according to the operating principle and function, and the analysis layer is defined and FMEA of each module is carried out to get fault mode sets and fault attributes. Then the key monitoring component is selected. Secondly, ESs are analyzed based on environ-

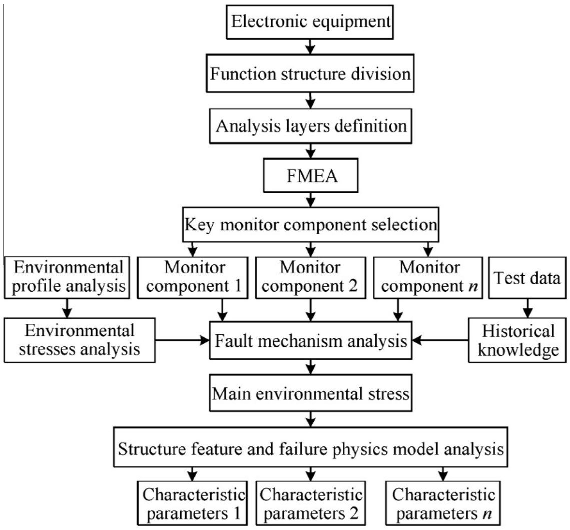

Fig. 1 Flow chart of MESs and KCPs selection.

mental profile. With the help of prior information, such as test data, historical knowledge, and failure analysis, fault mechanism is analyzed and summarized. Then, MESs can be obtained. Finally, integrating MESs with the structure feature and failure physics model of components, KCPs can be selected. Thereafter, an FMMEA table can be created which includes the fault modes, mechanisms, ESs analysis results, and so on.

3. Association model between integrated environmental stress event and BIT output

3.1. Reference stress events division

The faults of electronic equipment are usually the outcome of combined effects of some MESs over a period of time.[9] Let weight vector $\boldsymbol{W}$ to express the impact of various MESs on faults, $\boldsymbol{W} = [w_1 w_2 \cdots w_n]$. We define the combined effects of some MESs as IES, from the above analysis, and then IES can be expressed as $\mathrm{IES} = \sum_{i=1}^{n} w_i p_i$. The faults induced by IES are typically partitioned as PFs, Ifs, and transient faults (TFs) according to their durations. Since TFs cannot be traced to a defect in a particular part of the system and, normally, their adverse effects disappear rapidly,[11–13] they are ignored in this paper, and TFs diagnosis can be found in Ref. [14]. So IES can be divided into three stress levels according to their impact on faults. We use normal stress events (NSEs), permanent faults stress events (PFSEs), and intermittent faults stress events (IFSEs) to denote the three stress levels, respectively. Each stress level corresponds to one stress event and different stress events lead to corresponding faults. Because IFs behavior often occurs intermittently, with fault events followed by corresponding "reset" events for these faults, followed by new occurrences of fault events, and so forth, IFs are assumed to be composed of present intermittent faults (PIFs) and reset intermittent faults (RIFs). Consequently, IFSEs are assumed to be composed of present intermittent faults stress events (PIFSEs) and reset intermittent faults stress events (RIFSEs), $\mathrm{IFSE} = \mathrm{PIFSE} \cup \mathrm{RIFSE}$. Each PIFSE has its corresponding RIFSE, while RIFSE cannot happen until PIFSE occurs at least once.[15]

In order to evaluate IES level, RSEs should be constructed first. Let $\mathbf{RSE}_i$ denote row vector, $\mathbf{RSE}_i = [\mathrm{NSE\ PIFSE\ PFSE}]$. We define the test stress value (TSV). When the TSV is less than the operating limit (OL), the equipment usually works normally; when the TSV is greater than the OL but less than the destroy limit (DL), the equipment may be faulty, but once the TSV returns to the OL, the fault is usually recoverable, namely, it is an IF; when the TSV is greater than the DL, then the fault is usually irreversible, namely, a PF occurs. The OL and DL of a module can be obtained in the design stage by reliability enhancement testing (RET). Then, RSEs can be expressed as

$$\mathrm{RSEs} = \begin{cases} \mathrm{NSE} & \text{if } |\mathrm{TSV}| < \mathrm{OL} \\ \mathrm{PIFSE} & \text{if } \mathrm{OL} < |\mathrm{TSV}| < \mathrm{DL} \\ \mathrm{PFSE} & \text{if } \mathrm{DL} < |\mathrm{TSV}| \end{cases} \tag{1}$$

3.2. Association model construction

A system which contains two aforementioned types of faults is considered in this paper. We assume IFs would not become PFs with a finite delay, which is usually true in reality. IES can be considered as an integrated environmental stress event (IESE), then $\mathrm{IESE} = \{\mathrm{NSE} \cup \mathrm{PFSE} \cup \mathrm{IFSE}\}$. Let ω be a trace, and the current fault (CF) may have four possible traces along the system evolution. This fact is illustrated in Fig. 2, where $\|s\|$ and $\|t\|$ are the lengths of traces s and t, respectively. ε denotes empty trace. We write "a fault occurs" means there is a trace of s that ends with IESE.

In ω_1 and ω_2, one can assert the occurrence of IFs, and in ω_4, one can assert the occurrence of PFs, but one cannot be certain of the fault types in ω_3.

In order to study evolution of the faults through IESE, the notion of labels is introduced to identify special changes in the states of system as in Refs. [15,16]. The labels are symbols that allow us to keep track of the occurrence of selected events along the system's evolution. We define PFs labels F_P, IFs labels F_I, PIFs labels F_IP, RIFs labels F_IR, $F_\mathrm{I} = F_\mathrm{IP} \cup F_\mathrm{IR}$, CF label F_C, because fault events are usually unobservable and it is difficult to recognize the types of CF when a fault occurs, $F_\mathrm{C} = F_\mathrm{P} \cup F_\mathrm{IP}$. System labels transformation through IESE are shown in Fig. 3.

As shown in Fig. 3, the fault and reset events occur with some regularity along any possible trace of the system. RIFSE is the last one to occur among PIFSE and RIFSE. While PIFSE leads system to an intermittent fault state, RIFSE returns it to its normal state, and PFSE leads whatever state of the system to a permanent fault state.[15] Therefore, integrating such regularity with IESE evaluation result can help recognize the corresponding fault types.

We define some subsets to show the system states transformation through stress events. This fact is illustrated in Fig. 4. In Fig. 4, some subsets are defined as follows: $X_{F_\mathrm{P}} \subseteq X_{F_\mathrm{C}}$, where F_C is PFs; $X_{F_\mathrm{IP}} \subseteq X_{F_\mathrm{C}}$, where F_C can be reset, and it may eventually become PFs; $X_{F_\mathrm{IR}} \subseteq X_\mathrm{N}$, it is defined as the states reachable from one state belonging to X_{F_IP}; $X_{F_\mathrm{C}} \subseteq X_i$,

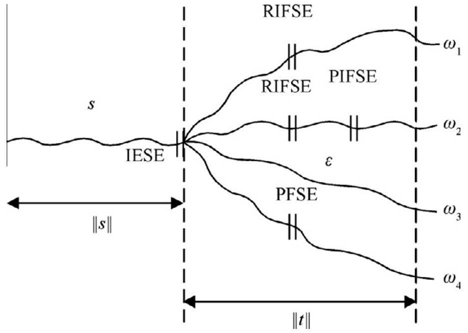

Fig. 2 All the possible traces of CF.

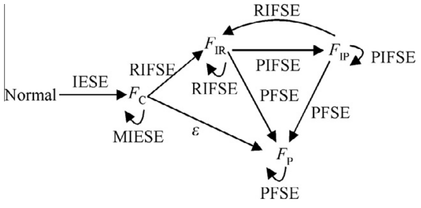

Fig. 3 System labels transformation through stress events.

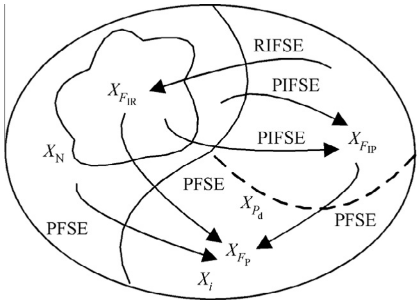

Fig. 4 System states evolution.

subset of current fault states, where $X_{F_{\mathrm{C}}} = X_{F_{\mathrm{P}}} \cup X_{F_{\mathrm{I}}}$; $X_{\mathrm{N}} \subseteq X_i$, subset of normal behavior states.

For it is difficult to diagnose IFs,[17] traditional BIT potentially presumes faults are persistent and doesn't take IFs into account. It classifies the line replaceable unit (LRU)/weapons replaceable assembly (WRA)/line replaceable module (LRM) behavior as good (OK) or faulted (hard).[1,18,19] When a fault is detected, it is assumed a PF (without analyzing whether it is or not) and two steps are usually carried out: A) locating the fault; B) correcting the fault. Correction is accomplished by repairing the fault or by replacing the faulty module with a fault-free one. It is common for modules to be replaced as faulty ones but later proved to be IFs.[5,13]

If the association model between IESE and BIT output can be established and the level of IES can be evaluated, then it is possible to help identify the type of a CF, especially an IF. In Fig. 2, we assume that a system is normal to start with, and when BIT indicates a fault, in order to assist identify the type of the CF, IESE is evaluated. If it is evaluated as PFSE, the fault can be diagnosed as a PF; if it is evaluated as PIFSE, then the fault can be considered as an IF; if the alarm disappear and IESE is evaluated as NSE, then we can assert the occurrence of IFs. Let AO denote association output result, then association model is built as follows

$$\mathrm{AO} = \begin{cases} \text{IFs} & \text{if IESE} = \{\text{NSE} \cup \text{IFSE}\} \\ \text{PFs} & \quad\text{if IESE} = \{\text{PFSE}\} \end{cases} \tag{2}$$

According to Eq. (2), one can see that IES levels evaluation is essential for association output.

4. Integrated environmental stress level evaluation

4.1. Integrated environmental stress level evaluation model

Integrated environmental stress value (IESV) is usually a continuous change in a range rather than a certain fixed value. We define the notation of interval number first.

Definition 1. Let R be the real line, an interval number or a closed interval is expressed as[20]

$$\widetilde{x} = [x^{\mathrm{l}}, x^{\mathrm{u}}] = \{x : x^{\mathrm{l}} \leqslant x \leqslant x^{\mathrm{u}}, x \in R\}$$

where x^{l} and x^{u} are the lower and upper limits of interval $\widetilde{x}$ on the real line R, respectively. Reference stress events matrix $\widetilde{\boldsymbol{A}} = [\widetilde{a}_{ij}]_{m\times n}$ is built by dividing each TSV into three stress intervals according to the OL and DL. $\widetilde{\boldsymbol{A}}$ is in the form of interval number.

$$\widetilde{\boldsymbol{A}} = \begin{array}{c} \\ \text{NSE} \\ \text{PIFSE} \\ \text{PFSE} \end{array} \begin{array}{c} \begin{array}{cccc} p_1 & p_2 & \cdots & p_n \end{array} \\ \begin{bmatrix} [a_{11}^{\mathrm{l}}, a_{11}^{\mathrm{u}}] & [a_{12}^{\mathrm{l}}, a_{12}^{\mathrm{u}}] & \cdots & [a_{1n}^{\mathrm{l}}, a_{1n}^{\mathrm{u}}] \\ [a_{21}^{\mathrm{l}}, a_{21}^{\mathrm{u}}] & [a_{22}^{\mathrm{l}}, a_{22}^{\mathrm{u}}] & \cdots & [a_{2n}^{\mathrm{l}}, a_{2n}^{\mathrm{u}}] \\ [a_{31}^{\mathrm{l}}, a_{31}^{u}] & [a_{32}^{\mathrm{l}}, a_{32}^{\mathrm{u}}] & \cdots & [a_{3n}^{\mathrm{l}}, a_{3n}^{\mathrm{u}}] \end{bmatrix} \end{array} \tag{3}$$

Here $m = 3$, and then the integrated stress level evaluation matrix $\overline{\boldsymbol{A}} = [\widetilde{a}_{kj}]_{(m+1)\times n}$ can be got by adding IESV into $\widetilde{\boldsymbol{A}}$ as the last row vector.[21]

$$\overline{\boldsymbol{A}} = \begin{array}{c} \\ \text{NSE} \\ \text{PFSE} \\ \text{PIFSE} \\ \text{IESE} \end{array} \begin{array}{c} \begin{array}{cccc} p_1 & p_2 & \cdots & p_n \end{array} \\ \begin{bmatrix} [a_{11}^{\mathrm{l}}, a_{11}^{\mathrm{u}}] & [a_{12}^{\mathrm{l}}, a_{12}^{\mathrm{u}}] & \cdots & [a_{1n}^{\mathrm{l}}, a_{1n}^{\mathrm{u}}] \\ [a_{21}^{\mathrm{l}}, a_{21}^{\mathrm{u}}] & [a_{22}^{\mathrm{l}}, a_{22}^{\mathrm{u}}] & \cdots & [a_{2n}^{\mathrm{l}}, a_{2n}^{\mathrm{u}}] \\ [a_{31}^{\mathrm{l}}, a_{31}^{\mathrm{u}}] & [a_{32}^{\mathrm{l}}, a_{32}^{\mathrm{u}}] & \cdots & [a_{3n}^{\mathrm{l}}, a_{3n}^{\mathrm{u}}] \\ [a_{k1}^{\mathrm{l}}, a_{k2}^{\mathrm{u}}] & [a_{k2}^{\mathrm{l}}, a_{k2}^{\mathrm{u}}] & \cdots & [a_{kn}^{\mathrm{l}}, a_{kn}^{\mathrm{u}}] \end{bmatrix} \end{array} \tag{4}$$

4.2. Interval grey association degree level evaluation algorithm

Because of various uncertain factors, the relationship between RSEs and IESE is ambiguous. Grey association analysis (GAA), which is an important part of the grey system theory, calculates the association degree of data series and figures out the relativity among factors. It doesn't require large samples and distribution of data and is ideally suitable to deal with the association relationship between two elements with uncertain and incomplete information.[20–22] The results of GAA have positive guidance in engineering. GAA has offered a new thought and method for system analysis. It has been applied successfully in many scientific and engineering fields, such as agriculture, hydrology, economics, geology, medicine, sociology, and so on.[22] In view of the above analysis, aiming at the interval number of IESV, a stress level evaluation approach based on interval grey association degree is proposed in this paper.

In order to avoid the differences of the interval numbers in quantity, unit, and type, the interval numbers should be normalized first. Usually, there are benefit criteria and cost criteria in multiple attribute decision making (MADM).[22] Toward profit criteria, the larger the criterion value is, the better the object is. For example, the higher the temperature value is, the more likely the chip is to fail. Thus, Eq. (5) is selected. Toward profit criteria, the smaller the criterion value is, the better the object is. The subscript sets for benefit criteria and cost criteria are denoted by I_1 and I_2, respectively. The elements in matrix $\overline{\boldsymbol{A}} = [\widetilde{a}_{ij}]_{(m+1)\times n}$ can be converted into corresponding ones in normalized stress level evaluation matrix $\widetilde{\boldsymbol{R}} = [\widetilde{r}_{ij}]_{(m+1)\times n}$ with the following equations, where $\widetilde{r}_{ij} = [r_{ij}^{\mathrm{l}}, r_{ij}^{\mathrm{u}}]$,

$$\begin{cases} r_{ij}^{\mathrm{l}} = a_{ij}^{\mathrm{l}} \Big/ \sqrt{\sum\limits_{i=0}^{m} \left(a_{ij}^{\mathrm{u}}\right)^2} \\ r_{ij}^{\mathrm{u}} = a_{ij}^{\mathrm{u}} \Big/ \sqrt{\sum\limits_{i=0}^{m} \left(a_{ij}^{\mathrm{l}}\right)^2} \\ \quad i \in M^*, j \in I_1 \end{cases} \tag{5}$$

$$\begin{cases} r_{ij}^{\mathrm{l}} = \left(1/a_{ij}^{\mathrm{u}}\right) \Big/ \sqrt{\sum\limits_{i=0}^{m} \left(1/a_{ij}^{\mathrm{l}}\right)^2} \\ r_{ij}^{\mathrm{u}} = \left(1/a_{ij}^{\mathrm{l}}\right) \Big/ \sqrt{\sum\limits_{i=0}^{m} \left(1/a_{ij}^{\mathrm{u}}\right)^2} \\ \quad i \in M^*, j \in I_2 \end{cases} \tag{6}$$

Definition 2. Let $\tilde{a} = [a^{\mathrm{l}}, a^{\mathrm{u}}]$ and $\tilde{b} = [b^{\mathrm{l}}, b^{\mathrm{u}}]$ be interval numbers, where $a^{\mathrm{l}} \leqslant a^{\mathrm{u}}, b^{\mathrm{l}} \leqslant b^{\mathrm{u}}, a^{\mathrm{l}}, a^{\mathrm{u}}, b^{\mathrm{l}}, b^{\mathrm{u}} \in R$, the distance $d(\tilde{a}, \tilde{b})$ between $\tilde{a}$ and $\tilde{b}$ is defined as follows[21]

$$d(\tilde{a}, \tilde{b}) = \frac{1}{\sqrt{2}} \sqrt{\left(a^{\mathrm{l}} - b^{\mathrm{l}}\right)^2 + \left(a^{\mathrm{u}} - b^{\mathrm{u}}\right)^2} \tag{7}$$

According to Definition 2, we can get the distance matrix $\boldsymbol{D} = [\boldsymbol{d}_{ij}]_{m \times n}$ between each RSE type and IESE type

$$d_{ij} = \frac{1}{\sqrt{2}} \sqrt{\left(r_{ij}^{\mathrm{l}} - r_{0j}^{\mathrm{l}}\right)^2 + \left(r_{ij}^{\mathrm{u}} - r_{0j}^{\mathrm{u}}\right)^2} \tag{8}$$

Definition 3. According to the grey system theory,[22] RSE types are considered as the reference sequences, and IESE type is considered as the comparative sequences, so the grey association coefficient between each RSE type and IESE type i defined as follows

$$\xi_{ij} = \frac{\min\limits_{i}\min\limits_{j}\{d_{ij}\} + \rho \max\limits_{i}\max\limits_{j}\{d_{ij}\}}{d_{ij} + \rho \max\limits_{i}\max\limits_{j}\{d_{ij}\}} \tag{9}$$
$$i = 1, 2, \cdots, m,\ j = 1, 2, \cdots, n$$

where ρ is the distinguishing coefficient and its value is usually taken as 0.5. The smaller its value is, the higher the distinguishing ability of the grey association coefficient is. We can obtain the matrix of the grey association coefficient as follows

$$\boldsymbol{\xi} = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \xi_{31} & \xi_{32} & \cdots & \xi_{3n} \end{bmatrix} \tag{10}$$

The weight of KCPs is used to express the different contributions to the faults. In order to avoid the subjectivity of weight selection, an entropy approach is introduced to compute the weight vector of various KCPs. Entropy is the measure of uncertainty degree of a system.[23] Entropy weight is dependent on the information amount delivered by KCPs. The larger the entropy weight is, the bigger the contribution of KCPs is.

Definition 4. According to the grey association coefficient matrix $\boldsymbol{\xi}$, the entropy of KCP is define as follows

$$H_j = -h \sum_{i=1}^{m} f_{ij} \ln f_{ij} \tag{11}$$

where $f_{ij} = \xi_{ij} / \sum_{i=1}^{m} \xi_{ij}, h = 1/\ln m$. When $f_{ij} = 0, f_{ij} \ln f_{ij} = 0$.

Definition 5. The entropy weight of KCP is defined as follows

$$w_j = (1 - H_j) / (n - \sum_{j=1}^{n} H_j)\ j = 1, 2, \cdots, n \tag{12}$$

According to Definition 5, entropy weight is dependent on the information of data itself. Therefore, it expresses the contribution of KCPs more objectively and factually. In order to discriminate how close IESE type is to RSE types, the grey association degree is defined as follows[24]

$$Z_i = \sum_{j=0}^{n} w_j \xi_{ij} \quad i = 1, 2, \cdots, m \tag{13}$$

The grey association degree Z_i reflects the similarity between IESE type and RSE$_i$ types. The larger Z_i is, the greater the similarity is. Namely, IESE belongs to RSE$_i$ when Z_i is the biggest.

From the above analysis, the process of IESE level evaluation algorithm is given as follows:

(1) Use Eq. (3) to construct reference stress event matrix from RET.
(2) Use Eq. (4) to establish integrated stress level evaluation matrix.
(3) Calculate the normalized stress level evaluation matrix according to Eq. (5) or Eq. (6).
(4) Compute the distance matrix between RSE types and IESE type according to Eq. (8).
(5) Obtain the grey association coefficient matrix according to Eq. (9).
(6) Determine entropy weights of KCPs according to Eq. (12).
(7) Calculate the grey association degree according to Eq. (13).

5. Case study

We illustrate our approach to IESE stress evaluation with an example of an aeronautic gyroscope. The functional structure of the gyroscope is shown in Fig. 5. The gyroscope can be divided into five functional modules, which are electronic static convertor, gyro motor, pendulum correction machine, gyroscope body and synchronous transmitter, and body resistance strengthen machine.[23]

The analysis layer is a shop replaceable unit (SRU). 13 kinds of main fault modes are got by the FMEA. The ESs include temperature, humidity, vibration, electronic stress, strike, load, electromagnetism, sand, salt, and contamination, which are described as ES$_1$, ES$_2$, ES$_3$, ES$_4$, ES$_5$, ES$_6$, ES$_7$, ES$_8$, ES$_9$, and ES$_{10}$, respectively. The FMMEA results of the gyroscope are shown in Table 1.

The optimized selections of MESs and KCPs of the electronic static convertor are discussed emphatically due to space limitations of the paper. From Table 1, one can find that the typical fault modes of the electronic static convertor are power tube breakdown and connector open, and temperature and vibration are the MESs. Considering the environmental profile

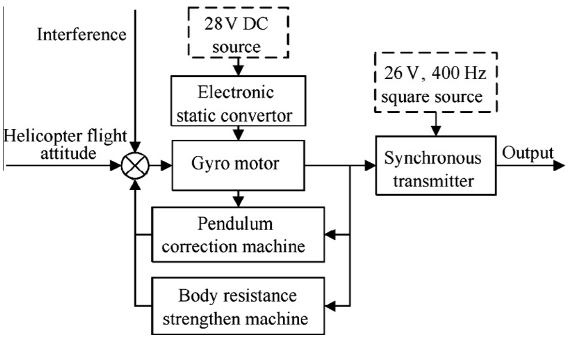

Fig. 5 Function graph of the gyroscope.

Table 1 FMMEA of the gyroscope.

Component	Fault location	Failure mode	Fault cause	Main stress	Criticality
Gyro motor	Winding	Turn-to-turn short	Insulation damage	ES_1, ES_4	II
		Turn-to-turn short	Insulation damage	ES_1, ES_4	II
		Ground fault	Insulation aging	ES_2, ES_3	II
		Phase open	Insulation aging	ES_1, ES_2, ES_4	II
	Iron core	Internal short	Insulation damage	ES_1, ES_3	II
		Core loosen	Bad fastening	ES_3, ES_5, ES_6	II
Body resistance	Motor	Motor fault	Fatigue damage	ES_1, ES_4	III
Strengthen machine	Switch	Sensor fault	Insulation aging	ES_1, ES_4	III
Pendulum correction machine	Axis	Bending and fracture	Bad installation	ES_1, ES_4	II
		Wear	Impurity wear	ES_1, ES_4	III
Synchronous transmitter	Transmitter	Output drift	Device aging	ES_1, ES_4, ES_7	II
Electronic static	Power tube	Breakdown	Overstress	ES_1, ES_4	II
Convertor	Connector	Open	Fatigue damage	ES_1, ES_3, ES_4	II

of a helicopter, vibration acceleration can be easily selected as a KCP. In order to make the power tube work normally, the ambient temperature should satisfy the following equation:

$$T_c = T_j - P_d \theta_c K \tag{14}$$

$$T_0 = T_c - T_s \tag{15}$$

where T_j is the junction temperature of the power tube, T_c the case temperature of the power tube, P_d the dissipated power, θ_c the crust thermal resistance, K the thermal time constant ($0 \leqslant K \leqslant 1$), T_0 the environmental temperature, and T_s the difference between the environmental and case temperatures of the power tube when a thermal balance state is reached. According to Eqs. (14), (15), we can find that high temperature is the main cause of power tube failures, so temperature value is selected as the other KCP. In this way, temperature value and vibration acceleration can be selected as the KCPs of the power tube.

An ADUC812 temperature sensor and an ADXL210 vibration sensor are adapted to measure temperature and vibration data, and the gyroscope has embedded BIT and diagnosis module. The OL and DL of each KCP of the electronic static convertor are obtained by RET. Environmental test of the gyroscope is shown in Fig. 6.

The reference stresses event matrix is built as follows

$$\widetilde{A} = \begin{array}{c|cc|} & p_1 & p_2 \\ \text{NSE} & -39.7\text{-}79.8 & 0\text{-}1.08 \\ \text{PFSE} & 79.8\text{-}85.3 & 1.08\text{-}1.19 \\ \text{PIFSE} & 85.3\text{-}123.4 & 1.19\text{-}1.89 \end{array}$$

where p_1 and p_2 stand for temperature value and vibration acceleration, respectively.

To validate the proposed approach in this paper, 15 sets of test data are selected to be analyzed. Let 0 and 2 denote OK and faulted BIT output, respectively. The interval grey association degrees are figured out according to Eqs. (5), (8)–(12), (and) (13). According to the interval grey association degree, IES level can be evaluated. The faults are to be confirmed once BIT indicates an alarm. Let 0, 1, and 2 represent OK, IFs, and PFs of actual and association output, respectively. Association outputs are given by integrating the stress level evaluation results with the BIT output according to Eq. (2). All the results of the electronic static convertor are listed in Table 2. In the table, Z_1, Z_2, Z_3 are the interval correlation parameters.

In Table 2, the wrong results are marked with overstriking. The outputs of BIT, actual, and association are shown in Fig. 7.

In Fig. 7, one can see that the traditional BIT cannot discriminate IFs from PFs. It never declares an IF when it occurs.

Table 2 Experiment results of the electronic static convertor.

Serial number	BIT output	Actual output	MIESV p_1 (°C)	MIESV p_2 (m/s^2)	Z_1	Z_2	Z_3	Level evaluation	Association output
1	0	0	−36.5–77.1	0–1.02	1.0000	0.5116	0.3696	NSE	0
2	2	**1**	79.1–84.8	0–1.02	1.4904	0.1387	0.2346	NSE	1
3	2	2	85.1–122.7	0–1.02	1.2079	0.4831	0.1706	PFSE	2
4	2	**1**	77.5–84.1	0–0.98	1.5336	0.1589	0.2550	PIFSE	1
5	2	**1**	77.5–84.1	0.95–1.12	0.4741	1.0000	0.4391	PIFSE	1
6	2	2	77.5–84.1	1.15–1.74	0.4233	0.6713	0.9400	PFSE	2
7	2	2	84.5–121.1	0–0.89	1.2624	0.6011	0.2083	NSE	1
8	2	**1**	84.5–121.1	0.92–1.07	0.5359	0.9640	0.5112	PIFSE	1
9	2	2	84.5–121.1 (1.08–1.69)	1.08–1.69	0.4617	0.6839	1.0000	PFSE	2
10	0	0	56.5–82.3	0–1.01	0.9885	0.5249	0.3806	NSE	0
11	2	**1**	56.5–82.3	1.02–1.10	0.4503	1.0000	0.4296	PIFSE	1
12	2	2	56.5–82.3	1.12–1.76	0.4332	0.6353	0.9633	PFSE	2
13	2	**1**	82.1–116.4	0–0.89	1.2872	0.5576	0.1724	NSE	1
14	2	**1**	82.1–116.4 (1.01–1.13)	1.01–1.13	0.4192	0.9617	0.4762	PIFSE	1
15	2	2	82.1–116.4	1.10–1.78	0.4107	0.5950	1.0000	PFSE	2

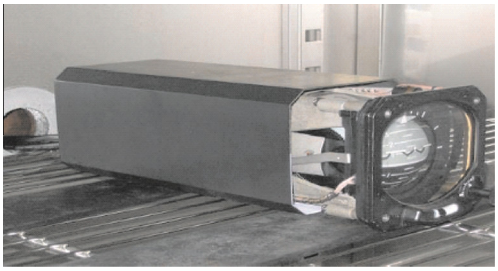

Fig. 6 Environmental test of the gyroscope.

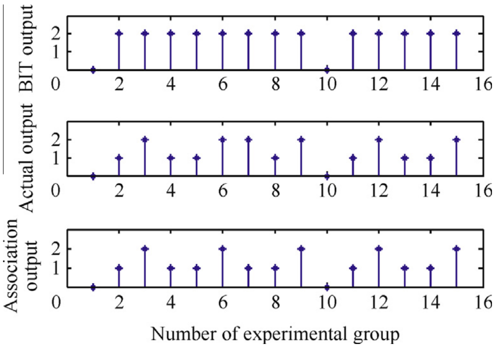

Fig. 7 Outputs of BIT, actual, and association.

IFs can be recognized by integrating BIT output with level evaluation result of IES. The false alarm rate (FAR) of the traditional BIT is 46.7%. In contrast, the FAR of association outputs drops to 6.7% under the same experimental conditions.

6. Conclusions

(1) A selection approach of MESs and KCPs based on FMMEA is presented that can provide a guide to address blindness in measuring and recording ESs.
(2) RSEs are constructed by dividing IES into three stress levels according to its impact on faults.
(3) An association model between IESE and BIT output is built.
(4) Due to interval number of IESV, an interval grey association approach is proposed to evaluate IESE level.
(5) A case is provided to validate and verify the proposed model and approach.

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