

Retraction

Retracted: A Three-Dimensional Complex Measurement Model-Based Avionic Radio-Frequency Power Source Health Assessment Method

Complexity

Received 19 December 2023; Accepted 19 December 2023; Published 20 December 2023

Copyright © 2023 Complexity. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

- (1) Discrepancies in scope
- (2) Discrepancies in the description of the research reported
- (3) Discrepancies between the availability of data and the research described
- (4) Inappropriate citations
- (5) Incoherent, meaningless and/or irrelevant content included in the article
- (6) Manipulated or compromised peer review

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

- [1] L. Huo, S. Li, S. Fei, and C. Lyu, "A Three-Dimensional Complex Measurement Model-Based Avionic Radio-Frequency Power Source Health Assessment Method," *Complexity*, vol. 2020, Article ID 6369729, 14 pages, 2020.

Research Article

A Three-Dimensional Complex Measurement Model-Based Avionic Radio-Frequency Power Source Health Assessment Method

Lin Huo ^{1,2}, Shiqi Li,¹ Simiao Fei,³ and Chuan Lyu⁴

¹School of Safety Engineering, Shenyang Aerospace University, Shenyang 110135, China

²Liaoning Key Laboratory of Aircraft Safety and Airworthiness, Shenyang, China

³Shenyang Aircraft Design Institute, Shenyang 110035, China

⁴Department of Reliability and System Engineering, Beihang University, Beijing 100191, China

Correspondence should be addressed to Lin Huo; huolin@buaa.edu.cn

Received 11 July 2020; Revised 5 September 2020; Accepted 18 September 2020; Published 19 October 2020

Academic Editor: Zhihan Lv

Copyright © 2020 Lin Huo et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Health assessment is an important part of PHM technology, which is crucial to product state monitoring and management. With the complexity of product structure and diversification of functions, the product health presents uncertainty under the complex influence of multiple factors. Nowadays, the general health assessment method is relatively simple and only considers the product function completeness, and the assessment effect accuracy still needs to be strengthened in the actual working environment. Most assessment parameters and assessment methods are selected ignoring the impact of environmental changes and operating time performance. Therefore, a new health measurement method for the avionic radio-frequency power source based on a three-dimensional complex measurement model is proposed. Firstly, the product health definition is proposed, and the health connotation is analyzed from three-dimensional aspects containing functional integrity, environmental adaptability, and temporal sustainability. According to the function and structure characteristics of radio-frequency power source, the health characterization parameters are then obtained and the health assessment parameter system is established. Finally, the three-dimensional complex measurement model is given, and the RF power source health assessment is carried out comprehensively from integrity, stability, and reliability aspects. The three-dimensional health assessment method provides a new way to solve the uncertainty of product health state under multiple factor effects, which is conducive to the targeted optimization management strategy.

1. Introduction

Prognostic and health management (PHM) technology refers to the use of advanced sensor integration, with the aid of various algorithms and intelligent models to diagnose, predict, and monitor the product health state and reasonably manage the product operation and maintenance so as to obtain the best product health state with the minimum investment. It has evolved from reliability analysis, testability design, fault analysis, and system health management [1]. With the economy development, people's living standards are constantly improving, and the safety awareness is also constantly improving. PHM technology is more and

more widely used, from the initial fighter field to the present civil aviation, aerospace vehicles, computer systems, large-scale mechanical equipment, nuclear power plants, complex product systems, and other fields.

Nowadays, the PHM technology system is developing towards a more intelligent, more precise, more comprehensive, and more convenient direction. Health management is an important part of PHM technology. Its purpose is to manage evaluation data, take proactive measures to monitor the complex product health state, and predict the performance change trend, failure time, and remaining useful life so as to take necessary measures to alleviate the complex product performance degradation [2]. As a state of

product, health has no clear definition, so the product health assessment method is different according to different people's understanding of health. According to the current research situation at home and abroad, health assessment methods are summarized into the following three categories: evaluation methods based on traditional methods, evaluation methods based on mathematical and physical models, and evaluation methods based on data.

Traditional health assessment methods include analytic hierarchy process (AHP), fuzzy theory and grey clustering theory, and so on. Wang et al. used the evaluation model combining fuzzy analytic hierarchy process, fuzzy preference programming, and order performance similarity ideal solution technology to evaluate the aeroengine health state [3]. Ren et al. combined grey clustering theory with rough set theory to form a fast and accurate fault classification decision-making method for numerical control machine tool health assessment [4]. Zhu and Song used cross fuzzy entropy to measure the similarity between test samples and normal samples and used similarity to evaluate the performance degradation state of bearings so as to complete the health state assessment of bearings [5]. Wang et al. combined the analytic hierarchy process (AHP) with variable weight processing to realize the comprehensive health assessment of diesel generator set operation state [6].

Health assessment methods based on mathematical and physical models include the application of Markov chain and so on. Allen et al. proposed a machine fault detection method using the hidden Markov model in process control, and the effectiveness of the method was illustrated by numerical calculation [7]. Bin et al. proposed a method combining Mahalanobis distance and histogram method to construct a complex system health assessment method for the comprehensive evaluation of system health state [8]. Liao et al. applied a new and flexible system or component prediction framework based on high-order hidden semi-Markov model (HOHSM) to assess the health state of NASA turbofan engine [9].

With the development of science and technology, artificial intelligence has become a hot spot of learning and is widely used in various fields; of course, the field of health assessment is no exception. For example, health assessment methods based on data are widely used. Samanta proposed the performance of artificial neural network and support vector machine in gear fault detection [10]. Xu et al. proposed a fault diagnosis method based on the fusion of neural network and D-S evidence theory to diagnose turbine fault [11]. Liu and Zio established a dynamic evaluation and fault prediction model of interconnected component system with noise monitoring data by using parallel Monte Carlo simulation and recursive Bayesian method [12]. Qin et al. developed a GIS equipment operation state analysis model based on machine learning algorithm and evaluated GIS equipment state according to the severity of PD [13]. Oluwasegun and Jung proposed a general framework based on discrete Bayesian network (BN), which is particularly suitable for decision fusion of heterogeneous prediction methods. BN parameters were calculated according to the fixed prognosis target. The validity of the proposed

prediction method based on decision fusion is proved by estimating the remaining useful life of turbofan engine [14]. Kexiong established a health assessment model of missile inertial navigation platform system by combining expert system with data driver according to the characteristics of a missile inertial navigation platform system [15]. Zhang et al. proposed a bearing health assessment method based on Hilbert transform envelope analysis and cluster analysis [16].

Most health assessment methods nowadays are based on the existing traditional assessment methods or modified by one or several methods. The assessment results are relatively simple, and the assessment effect accuracy still needs to be strengthened in the actual working environment. Most parameters are selected according to the product characteristics, ignoring the impact of environmental changes and operating time on product performance.

In this paper, a new multidimensional health assessment method is proposed to evaluate the health of a certain avionic radio-frequency (RF) power source. The model is built from three dimensions of functional integrity, environmental adaptability, and temporal sustainability. The health of the equipment is described comprehensively from three aspects of integrity, stability, and reliability so that the health level is no longer one plane point line, but a number of three-dimensional verticals. It provides a new idea to solve the uncertainty of product health state under the effects of multiple factors, which is conducive to the formulation of health optimization management strategy.

2. Health Connotation and Three-Dimensional Complex Measurement Model

Combined with the modern product characteristics, such as diversified functions, changeable use environment, and complex structure levels, product health is defined as the product ability degree/state to continuously respond to the environment and complete the specified tasks. When the product function is intact, only with good sustainability and stability can the product be in the best state. Otherwise, it may reduce or damage the function and cause failure. Therefore, a product in a healthy state should not only have good functions to ensure its ability to perform tasks but also maintain the stability of function, internal structure, and organization for a long time and have certain adaptability to environmental effects. Therefore, the meaning of health is diverse and extensive. The composition of product health should include functional integrity, temporal sustainability, and environmental adaptability.

In general, the changes of product health state are functional failure, sustainability, and the decline of adaptability to the external world. It has two interrelated characteristics: the increase of failure rate with time and the decline of adaptability to environmental changes. Therefore, focusing on three aspects of product health, a product health three-dimensional spatial measurement model is proposed, and the parametric modeling method is studied from the three dimensions of function, environment, and time. Among them, functional integrity is more focused on whether the function of the product can be realized,

temporal sustainability can be considered from the perspective of reliability and failure rate, and the essence of environmental adaptability is to investigate the stability of product performance in a certain environment. Therefore, the research of RF power source health measurement is to study whether the function of RF power source is complete, whether it has certain anti-interference stability, and how long it can work continuously without fault.

2.1. Functional Integrity Dimension. In these three aspects, the functional completeness and integrity is the basis of health. The most basic requirement of a healthy product is to be able to realize all its functions normally. The so-called function refers to the ability that a product should have when it runs normally. It is an abstract description of the tasks that a product can accomplish. It describes the inherent health capability of a product from a static state. The functional integrity of a product directly shows whether the product function can be fully realized. Therefore, the functional integrity C of the product is taken as the measurement index of its functional integrity, and the importance of each function is taken as the weight to measure the conformity between the functions and the complete functions of the product at the present stage, that is, the functional coverage rate, as shown in Figure 1. The value range of health degree is $[0, 1]$. When the research object meets all the design requirements (such as functional integrity, environmental adaptability, and temporal sustainability), the health degree is 1, which indicates a technical state that fully meets the design requirements. When the product fails to reach the required health level, the health degree is 0, and the product is in a complete failure state. The intermediate state is a subhealthy state with some defects. In practical application, we understand “the health degree state 1” as “the health design state value 1”.

Suppose that the product has m functions F_i , and the relationship between the functions is clear; let the importance weight of each function $\omega_i \in [0, 1]$, $i = 1, 2, \dots, m$. Because the relationship between product functions directly affects the realization of the whole function, the expression of function integrity is different according to different functional relationships.

- (1) When the function relationship is in series, the functions are interrelated and indispensable. As long as one function fails, the realization of the function will be affected and the whole function cannot be realized. The product functional integrity is expressed as

$$C = \prod_{i=1}^m \|F_i\|, \quad (1)$$

$$\|F_i\| = \begin{cases} 1, & F_i \text{ function implementation,} \\ 0, & F_i \text{ function not implemented,} \end{cases} \quad i = 1, 2, \dots, m.$$

- (2) When the function relationship is in parallel, each function relationship is independent. As long as one function can be realized, it will not affect the realization of the whole function. However, the failure of multiple functions will directly lead to the decline of the product health state and reliability. It can be seen in product with reconfiguration and spare parts structure. The function integrity of the product is expressed as

$$C = \sum_{i=1}^m \omega_i \|F_i\|, \quad (2)$$

$$\|F_i\| = \begin{cases} 1, & F_i \text{ function implementation,} \\ 0, & F_i \text{ function not implemented,} \end{cases} \quad i = 1, 2, \dots, m.$$

In general, the functions of a product are not only in series or in parallel. In this case, according to the specific product function relationship or task reliability block diagram, the correlation of the functions should be analyzed, and the functional integrity expression can be obtained. However, when the product functional structure is more complex, especially for some complex electromechanical product, it is impossible to give a clear functional relationship. Then, the characterization parameters describing the product function can be used as variables to measure the conformity between the function and the functional integrity of the product at this stage, and the overall functional integrity of the product can be obtained.

Assuming that the characterization factor of product function is f , the expression form of product functional integrity C is

$$\forall C \in [0, 1], \quad \text{s. t. } X_F \vartheta C, \quad (3)$$

$$C = \vartheta[X_F - T], \quad (4)$$

where X_F is the parameter representing the functional state of the product; T is the standard parameter with full functionality corresponding to parameter X_F and $\vartheta(\cdot)$ is the functional deviation function; $\vartheta: X_F | R \rightarrow h_f | [0, 1]$ indicates that the mapping ϑ projects the functional characterization parameter X_F into a real number of $C \in [0, 1]$.

The projection of X_F is a real number of $C \in [0, 1]$.

In some complex conditions, when the product monitoring data are difficult to obtain, it is impossible to measure the environmental adaptability or temporal sustainability, and the product health can also be simplified as functional integrity assessment.

2.2. Environmental Adaptability Dimension. Health is not just the synonym of good function. Healthy product can maintain the stability of function and structure for a long time and can realize all the predetermined functions, performance, or the ability not to be destroyed under the interference of external environment, that is, it has the ability

to adapt to the environment. Currently, healthy subjects with normal parameters are likely to have fatal problems once they are disturbed or changed due to lack of environmental adaptability.

Product environmental adaptability refers to the product ability to realize all its functions (properties) and not be damaged under the influence of various environments expected to be encountered in its life cycle, which is an important product quality characteristic [17]. It is inseparable from health. Environmental adaptability reflects the adaptability and stability of product function and performance to environmental changes, while functional integrity is to investigate whether the product can meet certain functional standards. In other words, the better the anti-interference and stability of the product under certain environmental conditions, the stronger the ability to maintain its structure and function and the stronger the environmental adaptability of the product. Therefore, product environmental adaptability is essentially to investigate the stability of the product health characterization parameters under the external environmental interference, that is, the noise cancelling ability.

The signal-to-noise ratio (SNR) of communication theory is introduced as a parameter index of product environmental adaptability. The signal-to-noise ratio (SNR) is the ratio of the effective part to the invalid part of the research object; it is commonly used in signal processing, speech recognition, image processing, and quality control [18–20]. Here, the output data of product health characterization parameters can be regarded as useful signal part, while the noise caused by environmental interference is useless signal part. The higher the SNR, the better the adaptability and anti-interference ability of the product to the external environment and the better the environmental adaptability of the product, and vice versa.

The signal-to-noise ratio (SNR), as a parameter to measure the ratio of useful signal to noise, originally came from the field of communication [18], which refers to the ratio of signal power/amplitude to total noise power/amplitude. The calculation formula is as follows:

$$\text{SNR} = \frac{P_S}{P_N} = \left(\frac{A_S}{A_N} \right)^2, \quad (5)$$

where P_S and A_S are signal power and amplitude and P_N and A_N are noise power and amplitude. In order to get the signal-to-noise ratio more intuitively, we need to convert the time-domain signal to the frequency domain, so we can calculate the signal-to-noise ratio S_N through Fourier transform, as shown in Figure 2.

$$S_N = \text{SNR} = \text{signal peak} - \text{noise floor} - 10 \lg N \text{ (dB)}, \quad (6)$$

where signal peak is the peak value of the signal; noise floor is the base of noise; and N is the number of samples.

2.3. Temporal Sustainability Dimension. The product health is closely related to its complete function, good stability, and sustainability, which is manifested in functional failure, increased failure rate with time, and decreased adaptability

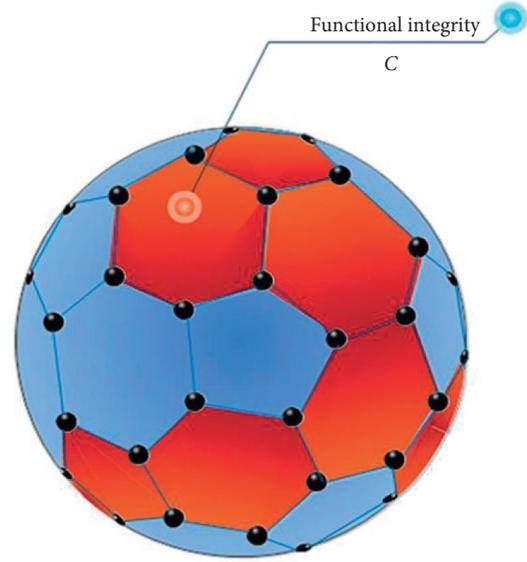


FIGURE 1: Schematic diagram of functional integrity.

to environmental changes. Good temporal sustainability can greatly increase the reliable time between failure so as to maintain the stability of its function and structure. Therefore, the product temporal sustainability is studied from the perspective of reliability.

In the theory of reliability, time is the core of reliability. Generally speaking, the longer the normal work (time between failure) is, the higher the reliability is. The definition of basic reliability in GJB451-90 refers to the product non-failure duration or probability under required conditions [21]. We hope that the product can continue to have the required capability for a period of time. The reliability function $R(t)$ precisely describes the possibility of the product to perform and maintain its function in a certain period of time $[0, t]$, as shown in Figure 3.

As shown in Figure 3, with the increase of operating or storage time, the reliability of the product decreases and the failure rate increases, which means that the continuous operation time of product reliability decreases and the temporal sustainability decreases. Therefore, from the perspective of time, reliability can fully reflect the continuous working ability. Therefore, this paper takes reliability as the measurement parameter index of temporal sustainability.

The higher the reliability $R(t)$ of the product is, the smaller the failure rate is, and the higher the probability that the product can maintain the required function in time $[0, t]$, the longer the sustainable working time is, that is, the better the product temporal sustainability; otherwise, the lower the reliability is, the shorter the product sustainable working time is and the worse the temporal sustainability is.

Therefore, through the use of functional integrity, signal-to-noise ratio, and reliability, a three-dimensional spatial model of RF power health is established, which comprehensively describes the health of RF power source from three aspects of integrity, stability, and reliability.

As shown in Figure 4, the health expression of the three-dimensional space of the RF power source is recorded as

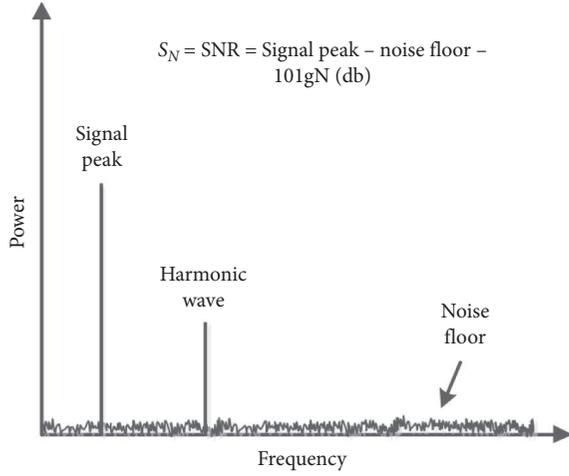


FIGURE 2: Schematic diagram of SNR calculation based on Fourier transform.

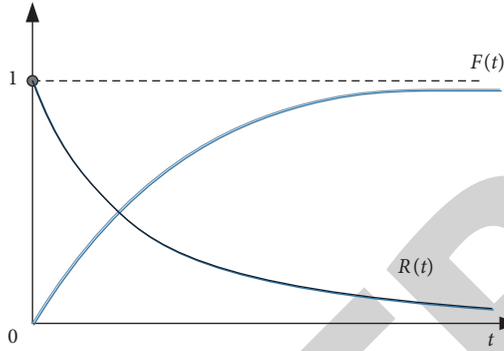


FIGURE 3: Reliability function and failure distribution function curve.

$$H_{\Delta} = (C, S_N, R), \quad (7)$$

where C is functional integrity; S_N is the signal-to-noise ratio; and R is the reliability.

$$H_i = \begin{cases} \{\text{unhealthy}\}, & \{[0, C_{\min}] \cup (-\infty, S_{\min}) \cup [0, R_{\min}]\}, \\ \{\text{subhealthy}\}, & 1 - \{[0, C_{\min}] \cup (-\infty, S_{\min}) \cup [0, R_{\min}]\} - \{[C_{\min}, +\infty) \cap [S_{\max}, +\infty) \cap [R_{\max}, +\infty)\}, \\ \{\text{healthy}\}, & \{[C_{\min}, +\infty) \cap [S_{\max}, +\infty) \cap [R_{\max}, +\infty)\}. \end{cases} \quad (9)$$

When the product can meet all the ability requirements of the three dimensions, the product belongs to the healthy state, that is, all of them reach or exceed the health threshold of the three dimensions $[C_{\max}, +\infty) \cap [S_{\max}, +\infty) \cap [R_{\max}, +\infty)$ —green space area; when at least one of the three dimensions does not reach the health limit and these three dimensions are above the abnormal threshold, then the product health is in the subhealthy state—yellow space area. As long as a dimension drops below the threshold of the exception, i.e., $[0, C_{\min}] \cup (-\infty, S_{\min}) \cup [0, R_{\min})$, the product is in a dangerous and unhealthy state—red space

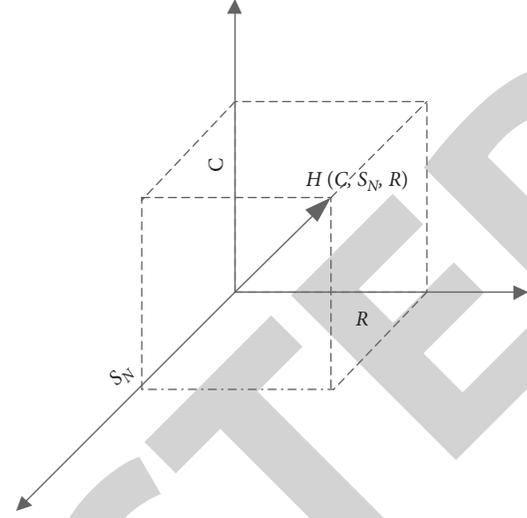


FIGURE 4: Three-dimensional health measurement model.

If the threshold range of the three dimensions of health is determined, respectively, the three levels can be divided into normal, dangerous, and abnormal (or failure).

$$C = \begin{cases} [0, C_{\min}), & \{\text{abnormal}\}, \\ [C_{\min}, C_{\max}), & \{\text{dangerous}\}, \\ [C_{\max}, +\infty), & \{\text{normal}\}, \end{cases} \quad (8)$$

$$S_N = \begin{cases} (-\infty, S_{\min}), & \{\text{abnormal}\}, \\ [S_{\min}, S_{\max}), & \{\text{dangerous}\}, \\ [S_{\max}, +\infty), & \{\text{normal}\}, \end{cases}$$

$$R = \begin{cases} [0, R_{\min}), & \{\text{abnormal}\}, \\ [R_{\min}, R_{\max}), & \{\text{dangerous}\}, \\ [R_{\max}, +\infty), & \{\text{normal}\}. \end{cases}$$

Therefore, it can be divided into three-dimensional health level space, as shown in Figure 5. The health degree of the product can be obtained as follows:

area; until the three dimensions are reduced to zero, the product develops to the state of complete failure.

3. Construction of Index System for Health Characterization Parameters of RF Power Source

The typical power module of a certain equipment RF channel system is selected as the research object. It is known that the power module, antenna interface module, frequency

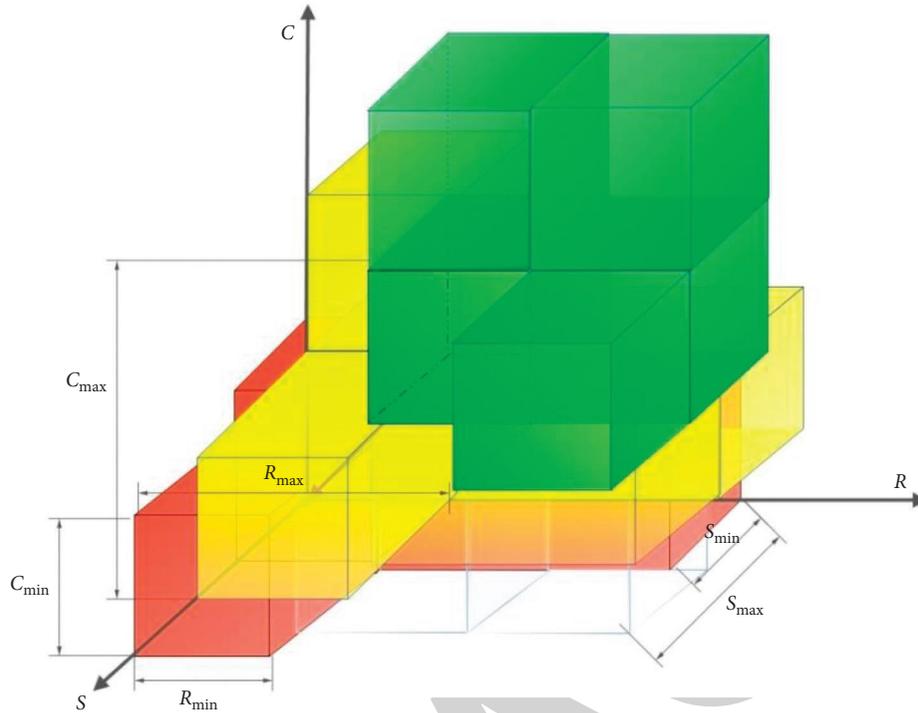


FIGURE 5: Three-dimensional spatial range of health degree.



FIGURE 6: A step-down power source product.

conversion channel module, digital interface, and processing module constitute the whole RF channel system. It is the total power source of each component module in the system. It completes the functions of signal receiving and sending, signal channel switching, signal frequency conversion processing, and signal preprocessing, commonly used in aerospace equipment such as aircraft.

The power module is a typical step-down power source product, as shown in Figure 6. It includes DC/DC converter and filter, which converts DC 270 V to DC 28 V and performs filtering output and provides overheating protection, overvoltage protection, and short-circuit protection.

3.1. Construction of RF Power Health Characterization. The key health characterization factors of RF power source were determined and screened step by step. The specific steps are as follows.

3.1.1. Defining the Research Object. The power source of RF system is taken as the research object. The indenture levels are as follows.

Initial indenture level: power module.

Minimum indenture level: constitutional unit:
 $P = \{p_i\}$, $i = 1, 2, \dots, 6$, including input filter circuit, DC/DC converter 1, DC/DC converter 2, output filter circuit 1, output filter circuit 2, and output filter circuit 3.

3.1.2. Dividing Product Levels. The power source module is divided into levels according to its structure and functional characteristics, and the hierarchical division diagram is shown in Figure 7.

3.1.3. Importance Analysis. The power source converts 270 V DC to 28 V DC output and provides overheating protection for DC/DC and short-circuit protection for input filter. The power source adopts the redundant form of dual DC/DC converters output in parallel and isolated from each other. That is to say, when two DC/DC converters work normally, they will share current output; when one DC/DC converter is damaged, the other one will output full power (500 W), which reduces the impact on the normal operation of power module. At the same time, 28 V DC at the output end is divided into two separate output channels. Among them, the output end of output filter 2 is the normal output end of power supply, while output filter 3 only provides a short-term power transfer of about 30 seconds through short-term capacitor storage when the normal power source

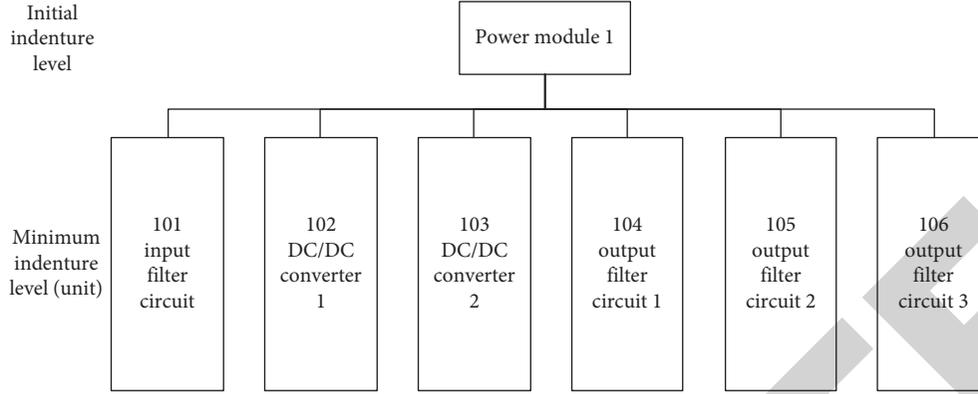


FIGURE 7: Schematic diagram of power module hierarchy.

terminal fails, which is not normally used. Its function diagram is shown in Figure 8.

The functional decomposition diagram of the power source product is shown in Figure 9.

According to the functional characteristics and engineering experience of step-down power source product, experts in the field scored each subfunction of the power module.

The difference in function importance of RF power source is not too big, and the number of subfunctions is not too much, so the 0–4 scoring method is used as the scoring standard [22]. The final scoring results are shown in Table 1.

Finally, the importance of each function of power module to the system is $I_1 = 0.46$, $I_2 = 0.29$, $I_3 = 0.11$, and $I_4 = 0.14$, as shown in Table 2.

The product function should be realized by the entity, and each subfunction is corresponding to its entity. As shown in the function decomposition in Figure 5, the function importance of the entity unit $P = \{p_1, p_2, \dots, p_6\}$ is expressed as

$$\begin{aligned}
 I_f(p_1) &= I_2 + I_4 \\
 &= 0.43, \\
 I_f(p_2) &= I_1 + I_4 \\
 &= 0.6, \\
 I_f(p_3) &= I_1 + I_4 \\
 &= 0.6, \\
 I_f(p_4) &= I_2 \\
 &= 0.29, \\
 I_f(p_5) &= I_2 \\
 &= 0.29, \\
 I_f(p_6) &= I_3 \\
 &= 0.11.
 \end{aligned} \tag{10}$$

Therefore, the function importance weight of each unit power module is $\delta_i(p_i) = I_f(p_i) / \sum_1^4 I_f(p_i)$, $i = 1, 2, \dots, 6$, i.e., input filter circuit, DC/DC conversion circuit 1, DC/DC conversion circuit 2, output filter circuit 1, output filter

circuit 2, and output filter circuit 3 are $\delta_i(p_i) = \{0.19, 0.26, 0.26, 0.12, 0.12, 0.05\}$.

According to the above importance analysis, all component objects $P = \{p_k\}$, $k = 1, 2, \dots, 6$ are sorted according to the importance of power module, and we get $P^* = \{\text{input filter circuit, output filter circuit 2, DC/DC conversion circuit 1, DC/DC conversion circuit 2, output filter circuit 1, output filter circuit 3}\}$. Output filter 3 only provides a short-term power transfer function for the power source when the normal output of the power source fails. Its state does not affect the normal operation of the power module, so the weight of the function importance is very small. Therefore, according to the requirements, we can focus on the key units of high importance for detailed characterization analysis.

3.1.4. Characterization Factor Analysis. In this paper, FMEA and failure rate statistical analysis are carried out for each key unit of power source module. Combined with engineering experience and expert opinions, the main failure modes, fault correlation, and monitoring parameters are determined. The simplified FMEA analysis table is shown in Figure 10.

Furthermore, according to the statistical failure rate distribution of historical fault case data, the frequency of DC/DC converter output failure accounts for the largest proportion of power system failure, and the failure modes of overheating protection, output short circuit, or output overvoltage caused by converter failure in DC/DC converter also occupy a large proportion. Therefore, power health characterization parameters mainly include DC/DC output voltage, ripple, insulation resistance, and module temperature.

Combined with domestic and foreign research, engineering experience, and expert opinions, six key functional units $P^* = \{p_i\}$, $i = 1, 2, \dots, 6$. According to the importance analysis, the importance of output filter 3 to the system is very low, which basically does not affect the normal operation of the power supply. Therefore, without considering the transient transfer function, the set of key health characterization factors can be expressed as $X_k = \{\text{power conversion efficiency } \eta, \text{ DC/DC1 temperature } T_1, \text{ DC/DC2 temperature } T_2, \text{ power output voltage } u, \text{ power output}$

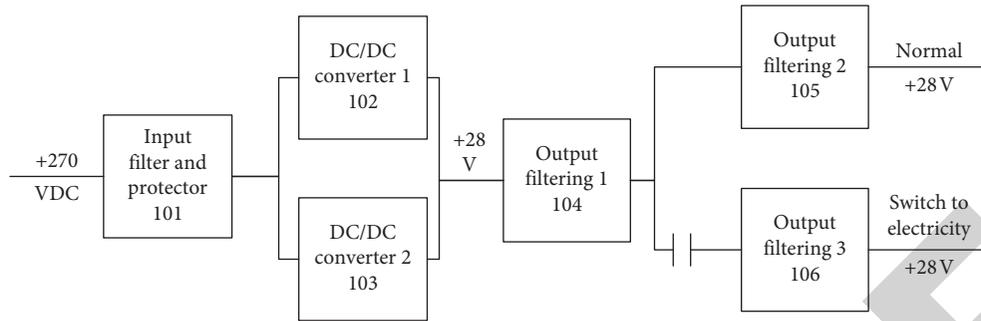


FIGURE 8: Functional block diagram of power source module.

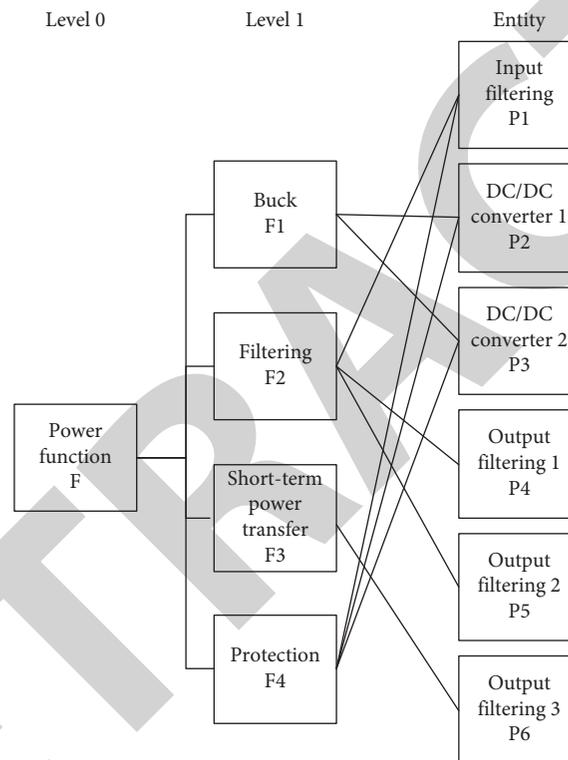


FIGURE 9: Functional decomposition diagram of power source module.

TABLE 1: 0–4 scoring standard table.

Comparison score k_i^j	Importance				
	A is much more important than B	A is important than B	A is as important as B	A is not as important as B	A is far less important than B
$A(k_A^B)$	4	3	2	1	0
$B(k_B^A)$	0	1	2	3	4

voltage ripple V }, which can cover or transform the above four factors greatly.

4. Health State Assessment of RF Power Supply

Product health includes functional integrity, temporal sustainability, and environmental adaptability. Among them, the integrity of functions is the foundation and main basis

for measuring the product health. Therefore, the health of RF power source is directly related to the completeness of its functions. In addition, it should have the stability to deal with all kinds of disturbances and be able to work reliably for a long time so as to achieve the health in a broad sense.

By using functional integrity, signal-to-noise ratio, and reliability, we establish a three-dimensional spatial model of product health in terms of function, environment, and time

TABLE 2: Functional importance based on functional decomposition.

	F1	F2	F3	F4	Accumulated score	Correction score	Functional importance I_i
F1	—	4	4	4	12	13	0.46
F2	1	—	3	3	7	8	0.29
F3	0	0	—	2	2	3	0.11
F4	0	1	2	—	3	4	0.14
Total					24	28	1.00

Note. In order to avoid zero score for the least important function, one point can be added to the cumulative score of each function as the correction score, and then the next step of calculation can be carried out.

Initial indenture level:

Power module

Minimum indenture level: unit

Code	Product or function unit name	Failure mode	Failure cause	Failure effect		SEV	Class	Fault correlation or detection parameters
				Local effect	Upper effect			
101	Input filter circuit	28V no output	Fuse FU1 open circuit; Diode V2 open circuit; Capacitor C1 ~ C5, C10 ~ C13 short circuit; L1 open circuit	The input filter circuit has no output	Power module 28V no output	III	E	Output voltage
		Output ripple overrun	Filter capacitor open circuit	Input filter circuit output ripple overrun	Nothing	IV	E	Output ripple
		Short circuit between output and housing	Capacitor C8, C9 short circuit	The output of the input filter circuit is short circuited to the housing	Power module electrical strength and insulation resistance index overrun	III	E	Insulation resistance and electrical strength
		Input reverse connection protection function failure	Diode V2 open circuit	Input filter circuit input reverse connection protection function failure	Power module input reverse connection protection function failure	III	E	Output voltage

FIGURE 10: The screenshot of FMEA.

and comprehensively describe the health of RF power source from three aspects of integrity, stability, and reliability. First of all, a high temperature test was conducted on a certain type of RF power supply. The duration was 72 hours. A group of health characterization parameter data of power source was collected every 20 minutes. Each group contained 5 key characterization parameter data. A total of 200 groups of observation sequence samples were collected. Among them, the first 20 groups of observation data under the initial normal state are taken as the health reference state data, and the last 180 groups of data are taken as the observation data under different test conditions.

4.1. Functional Integrity. Suppose that the main function of the power source is F_i , $i \in R$, including step-down, filtering, overheating, and short-circuit protection. To judge whether its function is in good condition, it can be obtained by detecting whether the voltage, ripple, and efficiency exceed the failure threshold. The functional integrity C is only divided into 0 and 1. However, when considering the short-term transfer function, it is also necessary to detect the voltage at the transfer terminal, so the basic characterization parameters of the power source are needed for the functional integrity. According to the previous function importance analysis, the function weights of step-down, filter, power

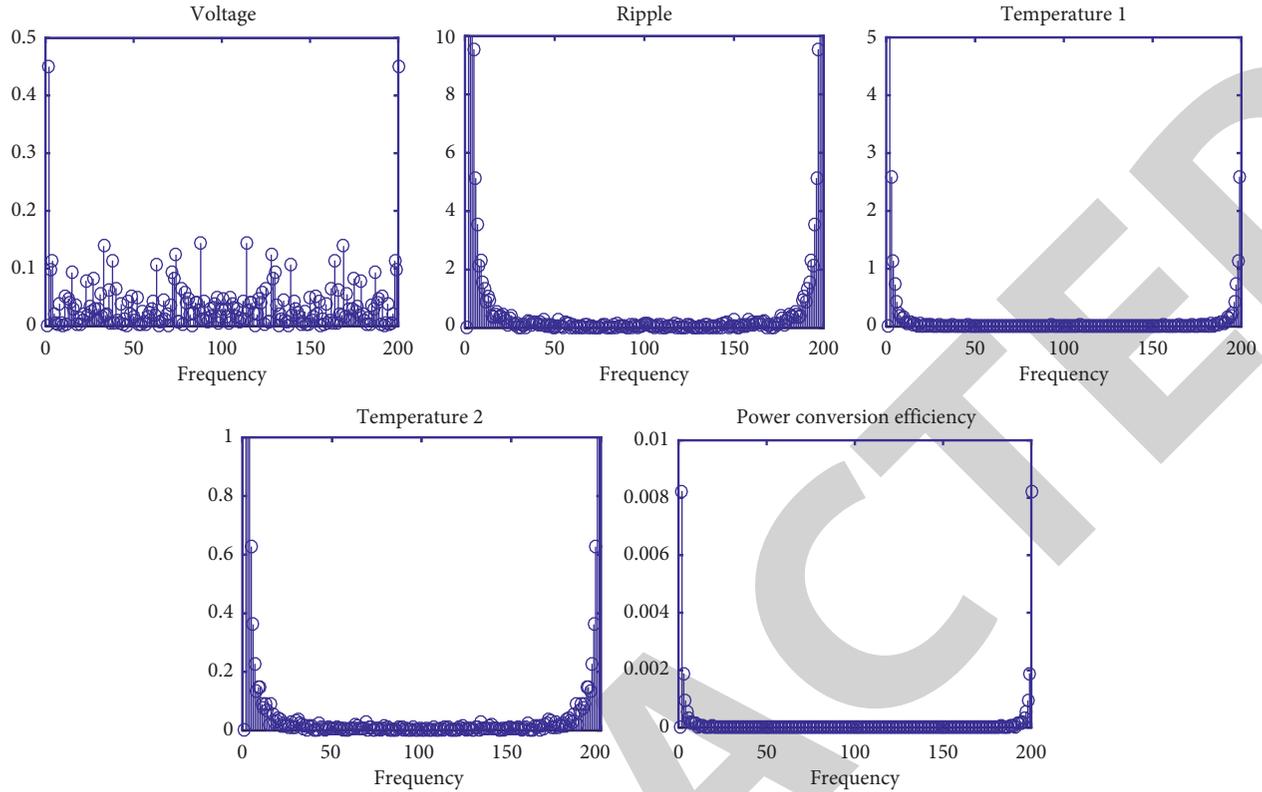


FIGURE 11: Power spectrum of power source key characteristic parameters based on fast Fourier transform.

transfer, and overheat protection are $I_1 = 0.46$, $I_2 = 0.29$, $I_3 = 0.11$, and $I_4 = 0.14$.

Therefore, the level threshold of functional integrity can be determined according to the importance of each function. When all functions can be executed normally, the functional integrity of the power source is 1; when the short-term power transfer function fails, the product function integrity can be determined by formula (2). By substituting the data into the above formula, it can be concluded that the power source functional integrity is 0.89. Obviously, the power

transfer failure does not affect the normal operation of the power supply, so 0.89 is taken as the threshold value of degradation stage; when the filtering function fails, the functional integrity decreases to 0.71, and the power source function is very incomplete, and the voltage output is unstable and close to the fault, which belongs to the upper limit of danger, and the step-down function fails. Therefore, it can be considered that when the functional integrity is 0.54, it has entered the area with the most incomplete function. The area is divided as follows:

$$C = \sum_{i=1}^4 I_i \|F_i\| = \begin{cases} \{0.89, 1\}, & \text{functionally intact,} \\ \{0.75, 0.86\}, & \text{functional decline,} \\ \{0.57, 0.60, 0.71\}, & \text{dangerous area,} \\ \{0, 0.11, 0.25, 0.40, 0.43, 0.46, 0.54\}, & \text{the lowest functional integrity.} \end{cases} \quad (11)$$

According to the 200 sets of characteristic parameter data collected in 72 hours, it is found that none of them has actually reached the failure threshold (such as output voltage less than 25V, greater than 29V, and ripple peak ≥ 120 mV), and there is no functional failure. Therefore, from the perspective of whether the overall function of the power

source can be implemented, the functional integrity has always been $\prod_{i=1}^4 \|F_i\| = 1$.

4.2. *Environmental Adaptability.* Taking the key health characterization parameters of the product as the time-domain

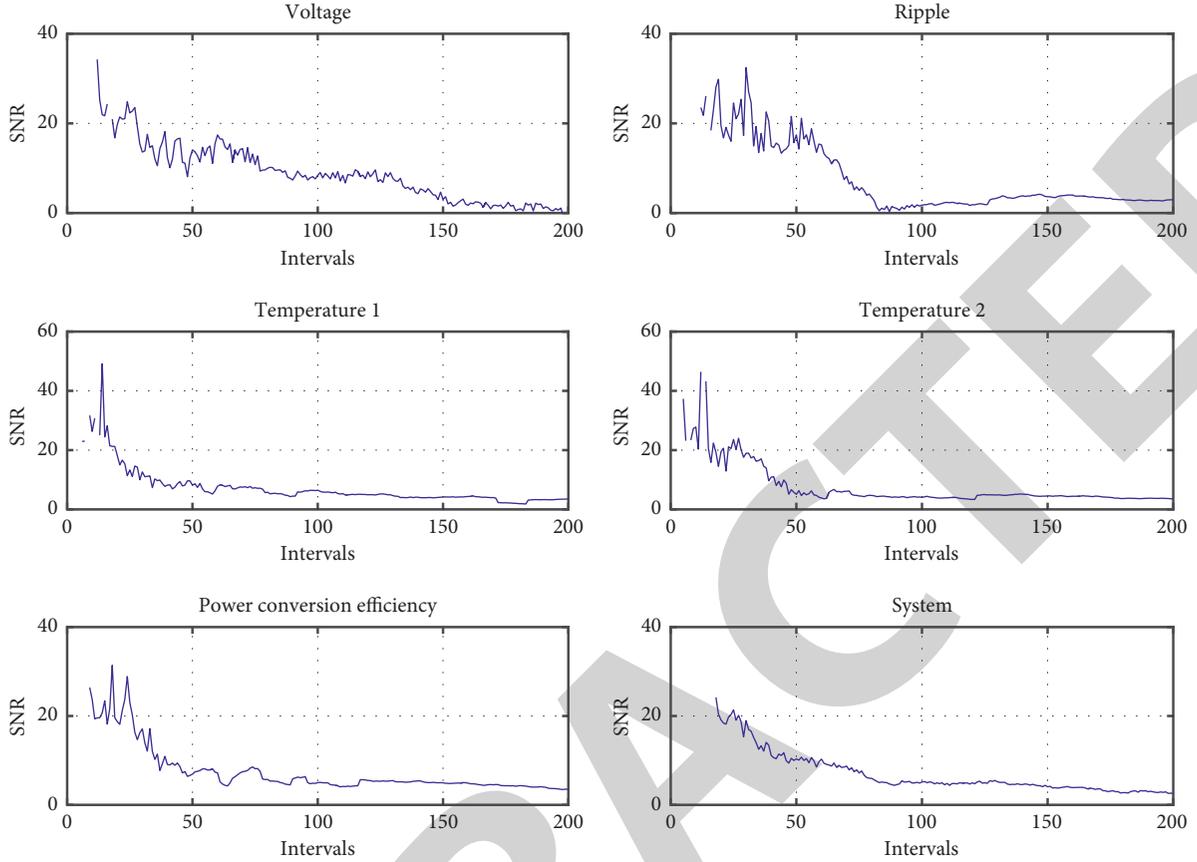


FIGURE 12: The power source key characteristic parameters and the system comprehensive signal-to-noise ratio curve.

signal, the health characterization parameters under the environment can be converted to the frequency domain through fast Fourier transform (FFT). The spectrum is shown in Figure 11.

According to formula (6), the SNR of each parameter is obtained, as shown in Figure 12.

The results show that when the power source is running at high temperature, the signal-to-noise ratio S_N shows a downward trend, indicating that the proportion of signal and noise of the product increases gradually, and the anti-interference and stability ability of the product to the environment gradually decreases, that is, the environmental adaptability decreases. It should be noted that from the beginning of sampling, the signal-to-noise ratio (SNR) presents a downward trend until it reaches the 40th sampling point. At this time, the signal-to-noise ratio (SNR) is about 14–16dB, and 15 dB is taken as the threshold value of SNR degradation stage; then, the downward trend gradually stabilizes until the sample points of 150–160th group decrease slowly, and the signal-to-noise ratio is about 3–6dB, so 5 dB is the signal-to-noise ratio with better environmental adaptability. According to the definition of SNR, when SNR is less than 0 dB, the signal is far less than noise, so 0 dB is taken as the worst threshold of environmental adaptability.

Thus, according to the signal-to-noise ratio, the level region of environmental adaptability can be determined. When the signal-to-noise ratio $S_N > 15$, the environmental adaptability is the best; when the signal-to-noise ratio

$5 < S_N \leq 15$, the environmental adaptability decreases, but it is acceptable; when the signal-to-noise ratio $0 < S_N \leq 5$, the product has low environmental adaptability and is in the dangerous area; when the signal-to-noise ratio $S_N \leq 0$, the environmental adaptability of the product is the worst and extremely unstable.

4.3. Temporal Sustainability. Temperature is one of the important environmental factors affecting product reliability. Research [23] shows that the failure rate of electronic product increases monotonously with temperature according to exponential law when the temperature is higher than general indoor environment temperature (about 20°C–25°C). It is known that the MTBF of the power source module is 718.7041 hours when it operates at 100°C high temperature. Since the power source belongs to electronic product, its service life generally follows exponential distribution, so

$$\begin{aligned}
 \lambda(t) &= \lambda, \\
 \text{MTBF} &= \frac{1}{\lambda}, \\
 R(t) &= e^{-\lambda t} \\
 &= e^{-t/\text{MTBF}},
 \end{aligned} \tag{12}$$

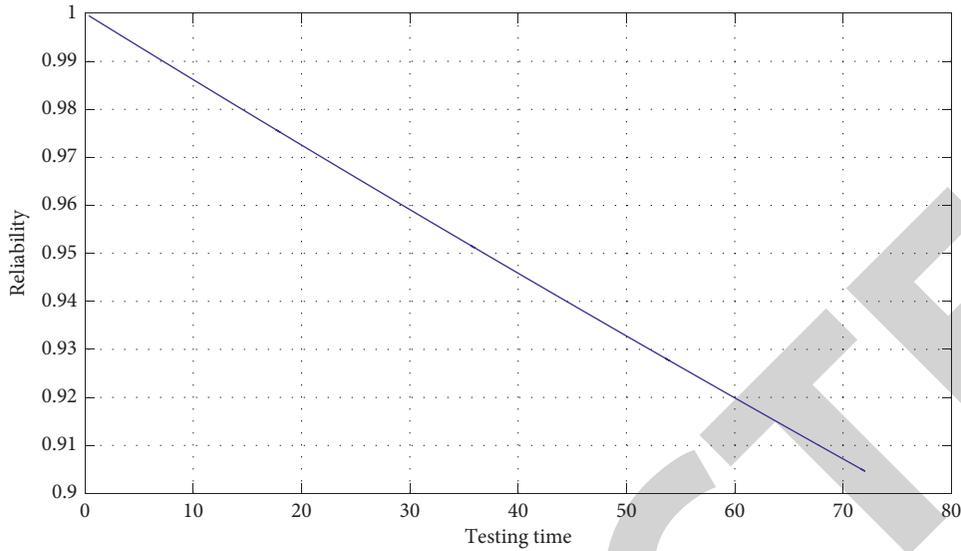


FIGURE 13: Reliability curve of aging test stage.

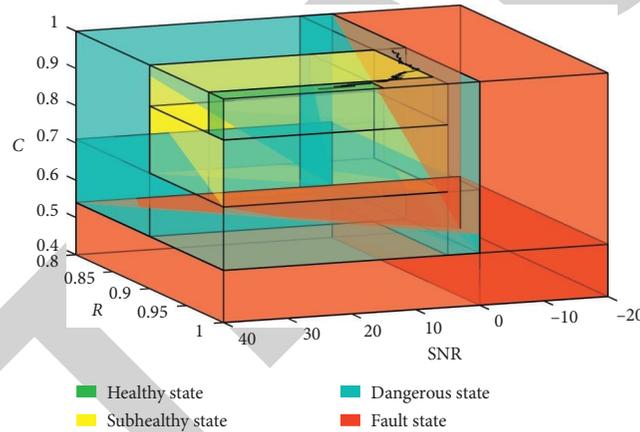


FIGURE 14: Health grade and health curve in three-dimensional space.

where $R(t)$ is the reliability and $\lambda(t)$ is the failure rate.

When there is a power supply, the failure rate can be approximated as

$$\lambda = \frac{1}{\text{MTBF}} = 1.3914 \times 10^{-3}, \quad (13)$$

and the power reliability function is obtained as follows:

$$R(t) = e^{-\lambda t} = e^{-1.3914 \times 10^{-3} t}. \quad (14)$$

According to the above reliability function, the reliability value of the corresponding time in 72-hour experiment is obtained, as shown in Figure 13.

With time increasing, the reliability decreases continuously, which indicates that the reliable continuous operation time is decreasing, so the product temporal sustainability

decreases. According to the engineering experience and the characteristics of electronic devices, the health threshold of reliability is 0.98, while for electrical devices, the product failure rate with reliability of 0.90 is quite high, so only the risk threshold is set as 0.90.

4.4. Three-Dimensional Complex Measurement Model.

Through the analysis of the above three dimensions, the health level area can be divided according to the parameter thresholds (functional integrity, signal-to-noise ratio, and reliability)—with three dimensions of functional integrity, environmental adaptability, and temporal sustainability. Therefore, the health level l can be divided into healthy state, subhealthy state, dangerous state, and fault state.

$$l = \begin{cases} \{1 \geq C > 0.89, S_N > 15, 1 \geq R > 0.98\}, & \text{healthy state,} \\ \{0.71 < C \leq 0.89, S_N > 5, 0.9 < R \leq 1\} \cup \\ \{0.71 < C \leq 1, 5 < S_N \leq 15, 0.9 < R \leq 1\} \cup & \text{subhealthy state,} \\ \{0.71 < C \leq 1, S_N > 5, 0.9 < R \leq 0.98\}, \\ \{0.54 < C \leq 0.71, S_N \geq 0, 0 \leq R \leq 1\} \cup & \text{dangerous state,} \\ \{0.54 < C \leq 1, 5 \geq S_N \geq 0, 0 \leq R \leq 1\}, \\ \{0 \leq C < 1, S_N < 0, 0 \leq R \leq 1\} \cup & \text{fault state.} \\ \{0 \leq C < 0.54, -\infty < S_N < +\infty, 0 \leq R \leq 1\}, \end{cases} \quad (15)$$

The RF power supply health level partition of the three-dimensional space is shown in Figure 14. At this time, the health level is no longer a plane point line, but a number of three-dimensional areas. The green area represents the healthy state, yellow represents the subhealthy state, blue represents the dangerous state, and red represents the fault state. According to the values of functional integrity C , signal-to-noise ratio S_N , and reliability R , a healthy three-dimensional spatial expression $H_\Delta = (C, S_N, R)$ can be obtained, as shown in the black curve in the figure, and then the health degree of the power source at each time can be determined according to the health level.

As can be seen from the above figure, with the power supply aging, the health curve of the three-dimensional space gradually changes from the initial green area to the yellow area and then to the blue area, which represents the gradual evolution of the health of the power source to subhealth and then to the dangerous state.

5. Conclusion

In this paper, a new three-dimensional complex measurement model-based avionic radio-frequency power source health assessment method is proposed. The functional integrity, signal-to-noise ratio, and reliability are taken as the parameter indexes of functional integrity, environmental adaptability, and temporal sustainability. Taking a certain RF power source as an example, the three-dimensional complex health assessment model which can clearly reflect the three dimensions of RF power source is then built, respectively. The proposed method also provides a new approach to solve the product health state uncertainty under multiple factor effects and optimization management for decision makers. However, further research can be carried out to find an accurate solution for threshold division in the process of health measurement.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

- [1] N. Fushun, "Some knowledge on fault prediction and health management technology," *Acta Instrumenta Sinica*, vol. 39, no. 8, pp. 1–14, 2018.
- [2] C. Deng, Y. Z. Sun, R. Li et al., "Hidden markov model based on the heavy-duty CNC health state estimate," *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, vol. 19, no. 3, pp. 552–558, 2013.
- [3] J. Wang, K. Fan, and W. Wang, "Integration of fuzzy AHP and FPP with TOPSIS methodology for aeroengine health assessment," *Expert Systems With Applications*, vol. 37, no. 12, 2010.
- [4] X. Ren, L. Chen, DeS. Li et al., "Fault decision of computer numerical control machine system using grey clustering analysis and rough set theory," vol. 11, no. 5, 2019.
- [5] K. Zhu and X. Song, "Cross-fuzzy entropy-based approach for performance degradation assessment of rolling element bearings," *Proceedings of the Institution of Mechanical Engineers*, vol. 232, no. 2, 2018.
- [6] D. Wang, H. Wang, Q. Wang, and H. Liu, "Comprehensive health assessment of marine diesel generator set based on analytic hierarchy process," *Electromechanical Equipment*, vol. 37, no. 3, pp. 53–58, 2020.
- [7] A. H. Tai, W.-Ki Ching, and L. Y. Chan, "Detection of machine failure: hidden markov model approach," *Computers & Industrial Engineering, Advances in Mechanical Engineering*, vol. 57, no. 2, 2008.
- [8] L. Bin, S. Dong, H. Lin et al., "Complex system health assessment based on Mahalanobis distance and bin-width estimation technique," *Chinese Journal of entific Instrument*, vol. 37, no. 9, 2016.
- [9] Y. Liao, Y. Xiang, and M. Wang, "Health assessment and prognostics based on higher order hidden semi-markov models," 2020, <http://arxiv.org/abs/2002.05272v1>.
- [10] B. Samanta, "Gear fault detection using artificial neural networks and support vector machines with genetic algorithms," *Mechanical Systems and Signal Processing*, vol. 18, no. 3, 2004.
- [11] C. Xu, H. Zhang, D. Peng, Y. Yu, C. Xu, and H. Zhang, "Study of fault diagnosis of integrate of D-S evidence theory based on neural network for turbine," *Energy Procedia*, vol. 16, 2012.
- [12] J. Liu and E. Zio, "System dynamic reliability assessment and failure prognostics," *Reliability Engineering and System Safety*, vol. 160, 2017.
- [13] F. Qin, J. Chen, X. Zhang, M. Jin, J. Zheng, and X. Li, "Research on GIS running state evaluation based on FKNN

- algorithm,” *Journal of Hubei University of Technology*, vol. 33, no. 2, pp. 62–66, 2018.
- [14] A. Oluwasegun and J.-C. Jung, “The application of machine learning for the Prognostics and Health Management of control element drive system,” *Nuclear Engineering and Technology*, vol. 52, 2020.
- [15] W. U. Ke-Xiong, W. Zhen-Hua, and S. Unit, “Health assessment and analysis method based on expert system and data driven,” *Heilongjiang Science*, vol. 10, no. 16, 2019.
- [16] X. Zhang, H. F. Sun, and J. X. ZhaoNi, “Bearing health assessment based on Hilbert transform envelope analysis and cluster analysis,” *International Journal of Reliability and Safety*, vol. 13, no. 3, p. 151, 2019.
- [17] B. Lu and Yi Hu, “Discussion on environmental adaptability evaluation technology of avionics,” *Science and Technology and Innovation*, vol. 6, no. 9, pp. 96-97, 2020.
- [18] H. Don, “Johnson. Signal-to-noise ratio,” *Scholarpedia*, vol. 1, p. 2088, 2006.
- [19] J. F. De Boer, B. Cense, B. H. Park, M. C. Pierce, G. J. Tearney, and B. E. Bouma, “Improved signal-to-noise ratio in spectral-domain compared with time-domain optical coherence tomography,” *Optics Letters*, vol. 28, pp. 2067–2069, 2003.
- [20] D. B. Hawkins and W. S. Yacullo, “Signal-to-Noise ratio advantage of binaural hearing aids and directional microphones under different levels of reverberation,” *Journal of Speech and Hearing Disorders*, vol. 49, pp. 278–286, 1984.
- [21] GJB451-90, *Terms of Reliability and Maintainability*, 1990.
- [22] W. Hongyan, “Application of 0-4 scoring method in technical and economic analysis of sewage treatment system,” *Science and Technology Innovation Guide*, vol. 14, no. 34, pp. 136–138, 2017.
- [23] X. Wang, Z. Ren, and Q. Wang, *Study On The Relationship Between Failure Mechanism And Environmental Stress Of Avionics*, pp. 120–124, Kunming, China, 2006.