Reliability Analysis of the Wet-end in Underwater Guard System

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Abstract. This paper presents the reliability analysis of the wet-end in underwater guard system. The difficulties in using active sonar in an underwater guard system include high reliability and the maintenance ability. The reliability block diagram of the system and main components was modeling, and the hazard rate of each PCB or Channel was predicted by part stress analysis. The reliability of different k/n redundancy configurations was calculated and compared with, then optimized the configuration of the component.

Introduction

It was suggested that a significant terrorist threat might be posed to domestic harbors in the form of an explosive device delivered underwater by a scuba diver. The underwater targets can be detected by acoustic equipment in underwater guard system.[1] In order to keep high continuance and accuracy, the wet-end of the underwater guard system must have a very high reliability.

Reliability is defined as the probability that a system (component) will function over some time period *t*. To express this relationship mathematically we define the continuous random variable *T* to be the time to failure of the system (component); T⩾0.Then the reliability can be expressed as

$$R(t) = \mathrm{P}\{T \geq t\}$$

Where $R(t) \geq 0$, $R(0)$=1, and $\lim_{t\to\infty} R(t) = 0$. For a given value of *t*, $R(t)$ is the probability that the time to failure is greater than or equal to *t*. [2]

The wet-end reliability goal for an underwater guard system is 0.95 at 1 year, which means $R(8760h) = 0.95$.

System Reliability Model

System Reliability block diagram

The Wet-end in Underwater Guard System is composed of power module, energy-storage module, signal process module, power amplifier module, signal receive module, signal-conditioning module and signal transmit module. The reliability block diagram of the wet-end is as fig.1.

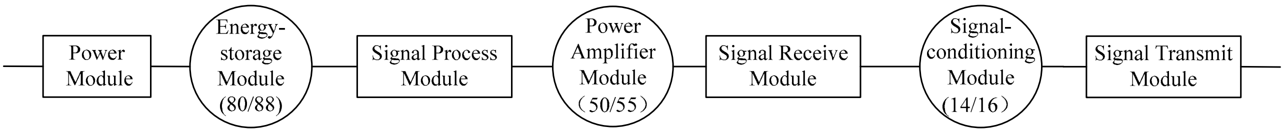

Fig. 1 reliability block diagram of the wet-end

The power module is composed of 3 PCBs (Printed Circuit Board) in parallel, which means that all PCBs must fail for the power module to fail. If one or more PCBs operate, the power module continues to operate.

All the redundancy modules in the system are designed to have 10% redundancy rate. The energy-storage module requires 80 out of its 88 energy-storage channels to operate in order to achieve orbit. The power amplifier module requires 50 out of its 55 channels function for the module to function. And the signal conditioning module requires 14 out of 16 channel to operate.

The signal process module, signal receive model and signal transmit model are in series, which all components must function for the system to function.

Since wet-end reliability goal is 0.95 at 1 year, and there are 7 modules in the system, each module reliability equally to be $0.95^{1/7} = 0.9927$.

Reliability Prediction of Each Board

The reliability of each component has been predicted by part stress analysis. And the results of the prediction are in table1.

Table 1 the reliability prediction results of each component

Name	Hazard rate ($10^{-6}h^{-1}$)	Type	Mission Time(h)	Mission Reliability
Power Board	5.6878	parallel (3)	8760	R_1
Energy-storage Channel	2.1565	80/88, Redundancy	8760	R_2
Signal Process Module	0.7023	serial, exponential	8760	R_3
Power Amplifier Channel	1.7789	50/55 Redundancy	8760	R_4
Signal Receive Module	0.3495	serial, exponential	8760	R_5
Signal Conditioning Channel	0.6610	serial, exponential	8760	R_6
Signal Transmit Module	0.5641	serial, exponential	8760	R_7

From the table 1, signal process module, signal receive module, and signal transmit module are in series. And the component failures are governed by the exponential failure law, then the reliability of the component can be calculated from Eq. 1. [3]

$$R(t) = \exp(-\int_0^t \lambda dt') = e^{-\lambda t} \tag{1}$$

λ, stand for the hazard rate. Obviously, the result of R_3, R_5, R_6 and R_7 can be calculated by Eq. 2-5.

$$R_3(8760) = e^{-\lambda_3 t} = e^{-0.7023\times10^{-6}\times8760} = 0.9939 \tag{2}$$

$$R_5(8760) = e^{-\lambda_5 t} = e^{-0.3495\times10^{-6}\times8760} = 0.9969 \tag{3}$$

$$R_6(8760) = e^{-\lambda_6 t} = e^{-0.6610\times10^{-6}\times8760} = 0.9942 \tag{4}$$

$$R_7(8760) = e^{-\lambda_7 t} = e^{-0.5641\times10^{-6}\times8760} = 0.9951 \tag{5}$$

The power module has 3 power boards in parallel, and each board is the same. The reliability of the power module can be calculated by Eq. 6.

$$R_1(8760) = 1- (1-e^{-\lambda_1 t})^3 = 1- (1-e^{-5.6878\times10^{-6}\times8760})^3 = 0.9999 \tag{6}$$

The energy-storage module and power amplifier module are in k/n redundancy, the reliability analysis of R_2, and R_4 will be analysis particularly in chapter 3 of this paper.

k/n Redundancy Reliability Analysis

k/n Redundancy Reliability Model

A generalization of *n* parallel components occurs when a requirement exists for *k* out of *n* identical and independent components to function for the system to function. The reliability block diagram of k/n redundancy is as fig.2.

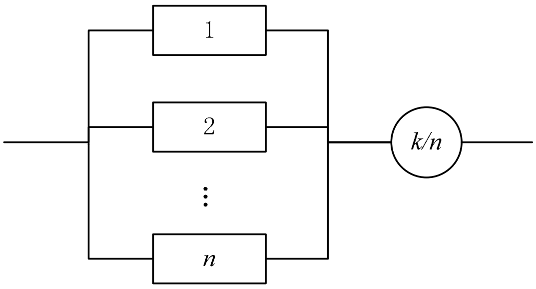

Fig.2 reliability block diagram of k/n redundancy

Obviously $k \leqslant n$. If k=1, complete redundancy occurs, and if k=n, the n components are, in effect, in series. The reliability can be obtained from the binomial probability distribution.

If each component is viewed as an independent trial with $R(t)$ (its reliability) as a constant probability of success, then

$$P(i)=C_n^i R^i(t)(1-R(t))^{n-i} \tag{7}$$

is the probability of exactly i components operating. C_n^i is the number of ways (arrangements) in which i successes (non-failures) can be obtained from n components. $R^i(1-R)^{n-i}$ is the probability of i success and n-i failures for a single arrangement of successes and failures. Therefore

$$R_s(t)=\sum_{i=k}^{n} P(i)=\sum_{i=k}^{n} C_n^i R^i(t)(1-R(t))^{n-i}\,. \tag{8}$$

In each module of the wet-end, the hazard rate of each channel is governed by exponential law, but hazard rate of the module would no longer be constant as it is a complex configuration, which is not in series. So the MTBF(Mean Time Between Failure) of the module isn't the multiplicative inverse of the hazard rate, it can be predicted by Eq. 9.

$$MTBF=\int_0^\infty R(t)dt=\int_0^\infty \sum_{i=k}^{n} C_n^i e^{-i\lambda t}(1-e^{-\lambda t})^{n-i}dt \tag{9}$$

Since

$$\begin{aligned}(1-e^{-\lambda t})^{n-i} &= C_{n-i}^0(-1)^{n-i}(e^{-\lambda t})^{n-i}+C_{n-i}^1(-1)^{n-i-1}(e^{-\lambda t})^{n-i-1}+\cdots+C_{n-i}^{n-i}(-1)^0(e^{-\lambda t})^0 \\ &= C_{n-i}^0(-1)^{n-i}e^{-n\lambda t+i\lambda t}+C_{n-i}^1(-1)^{n-i-1}e^{-n\lambda t+i\lambda+\lambda t}+\cdots+C_{n-i}^{n-i}\end{aligned}, \tag{10}$$

The Eq. 9 can be infferred as Eq. 11.

$$\begin{aligned}MTBF &= \int_0^\infty R(t)dt=\int_0^\infty \sum_{i=k}^{n} C_n^i e^{-i\lambda t}(1-e^{-\lambda t})^{n-i}dt \\ &= \int_0^\infty \sum_{i=k}^{n} C_n^i e^{-i\lambda t}[C_{n-i}^0(-1)^{n-i}e^{-n\lambda t+i\lambda t}+C_{n-i}^1(-1)^{n-i-1}e^{-n\lambda t+i\lambda+\lambda t}+\cdots+C_{n-i}^{n-i}]dt \\ &= \sum_{i=k}^{n} C_n^i[C_{n-i}^0(-1)^{n-i}\int_0^\infty e^{-n\lambda t}dt+C_{n-i}^1(-1)^{n-i-1}\int_0^\infty e^{-n\lambda t+\lambda t}dt+\cdots+C_{n-i}^{n-i}\int_0^\infty e^{-i\lambda t}dt] \\ &= \sum_{i=k}^{n} C_n^i(C_{n-i}^0(-1)^{n-i}\frac{1}{-n\lambda}+C_{n-i}^1(-1)^{n-i-1}\frac{1}{(-n+1)\lambda}dt+\cdots+C_{n-i}^{n-i}\frac{1}{-i\lambda})\end{aligned} \tag{11}$$

Reliability Prediction of the Power Amplifier Module

The power amplifier module requires 50 out of its 55 channels function for the module to function, and the reliability block diagram of the module is as fig.3.

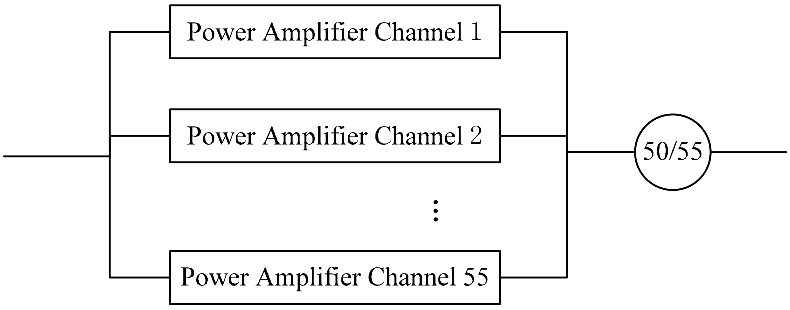

Fig.3 reliability block diagram of power amplifier module

As each channel is same and the failure distribution is exponential, the hazard rate of each channel is constant, the reliability of each channel can be calculate from Eq. 1. When t=8760, $\lambda_{4c} = 1.7789 \times 10^{-6} h^{-1}$, the reliability of each power amplifier channel is $R_{4c}(8760) = e^{-\lambda_{4c}t} = 0.9845$.

The reliability of k/n redundancy can be calculate from Eq. 8, and the reliability of the module is R_4 as Eq. 12.

$$R_4(t) = \sum_{i=k}^{n} C_n^i R^i(t)(1-R(t))^{n-i} = \sum_{i=50}^{55} C_{55}^i R_{4c}^i(t)(1-R_{4c}(t))^{55-i} \tag{12}$$

Using Matlab program can get the result of Eq. 12. is $R_4(8760) = 0.9998$.Then the MTBF of the power amplifier module can be calculated by Eq. 13.

$$MTBF = \sum_{i=50}^{55} C_{55}^i (C_{55-i}^0 (-1)^{55-i} \frac{1}{-55\lambda_{4c}} + C_{55-i}^1 (-1)^{55-i-1} \frac{1}{(-55+1)\lambda_{4c}} dt + \cdots + C_{55-i}^{55-i} \frac{1}{-i\lambda_{4c}}) \tag{13}$$

The result for the MTBF of the power amplifier module that can be generated through computer programs is $64313h$.

Optimization of the Configuration of the Energy-storage Module

The energy-storage module requires 80 out of its 88 energy-storage channels function for the module to function. Since the hazard rate of each channel is $2.1565 \times 10^{-6} h^{-1}$, follow the Eq. 8 and Eq. 11, can get the reliability and MTBF for the 80/88 redundancy configuration. Besides, as the module requires 80 channels to function, the results when total channels from 85 to 91 are compared in table 2.

Table 2 the prediction for different kinds of redundancy

No.	k/n redundancy Type	Mission Reliability	MTBF(h)
1	80/85	0.9947	33739
2	80/86	0.9988	39131
3	80/87	0.9998	44461
4	80/88	0.9999	49726
5	80/89	0.9999	54900
6	80/90	0.9999	59030
7	80/91	0.9999	56211

When energy-storage module is designed to have 10% redundancy-80/88 redundancy, the reliability of the module is 0.9999. The reliability allocated equally to each module is 0.9927, and the reliability of energy-storage module should be no less than the value. When the redundancy is 80/88, the reliability is slightly higher, and that will be a waste for the system. From table 2, when choose 80/85 redundancy, the reliability ($R_2(8760) = 0.9947$) is appropriate.

System Reliability Prediction

From the analysis presented above, we concluded the results of the reliability prediction in table 3.

Table 3 the reliability prediction results of each module

Name	Hazard rate ($10^{-6}h^{-1}$)	Mission Time(h)	Mission Reliability
Power Board	5.6878	8760	0.9999
Energy-storage Channel	2.1565	8760	0.9947
Signal Process Module	0.7023	8760	0.9939
Power Amplifier Channel	1.7789	8760	0.9998
Signal Receive Module	0.3495	8760	0.9969
Signal Conditioning Channel	0.6610	8760	0.9942
Signal Transmit Module	0.5641	8760	0.9951

So we can predicts the reliability of the wet end

$$R_s(8760) = \prod_{i=1}^{7} R_i = R_1 R_2 R_3 R_4 R_5 R_6 R_7 = 0.9748 .$$

The result meets the requirement of the reliability goal, which is 0.95 at 1 year.

Conclusions

This paper discusses the mission reliability of the wet-end in underwater guard system, and the complexities associated with the k/n redundancy. The presented method of the k/n redundancy reliability prediction is based on the exponential failure law of each channel. Through the comparison of the different configuration of the k/n redundancy, the energy-storage module and the power amplifier module are optimized. Then the reliability of the wet-end is predicted

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