Research on Life Assessment Method of Spacecraft Optical Cable Based on Degradation Data

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***Abstract*—Optical cable communication is an important development direction of spacecraft bus transmission due to its advantages of large capacity, light weight and low loss. This paper introduces the structure of optical cables for spacecraft and summarizes the main failure modes. During the on-orbit service, the product characteristics tend to deteriorate with the increase of service time. Loss coefficient is a sensitive parameter to characterize the degradation process. That is, loss coefficient has obvious degradation in the lifetime. In view of the degradation behavior, the loss coefficient is taken as the sensitive degradation parameter. The data obtained from accelerated test are used to establish the performance degradation model of optical cables, to clarify the degradation law. The particle filter method is used to predict the degradation trend and the service life, so as to provide guidance for engineering application.**

Keywords-Optical cable; degradation; life assessment; particle filter; loss coefficient

I. Introduction

With the increasing requirement of fast data transmission, processing and inter-satellite and inter-satellite-to-ground exchange in spacecraft, higher requirements are put forward for bus transmission. Compared with traditional cable bus, optical cable communication has the advantages of large transmission capacity and high stability, and is an important development direction of spacecraft data bus transmission. Taking China's space station as an example, the total demand for optical cables is expected to reach more than 6000 m, and the service life of optical cables is not less than 15 years. Although optical cable communication applications have been successfully developed in some satellites in China, the on-orbit lifetime of these satellites is relatively short, and there is no validation data for long-life applications of optical cable. A lot of research on the reliability and lifetime of optical cables for spacecraft has been carried out abroad, and they have been widely used. A lot of experience and data have been accumulated in long-life applications on orbit. However, there is a big gap between our country's optical cables for spacecraft and foreign products in terms of material and technology. Therefore, we can't simply use foreign test data to guide domestic work. It is urgent to carry out long-life verification technology research for domestic optical cables for spacecraft.

II. Structure and Characteristics of Optical Cable

Optical cables are mainly composed of optical fibers and protective structures. They are usually coated with buffer layer and outer sheath outside the optical fibers to form cable-forming products with certain mechanical strength and environmental resistance[1]. Optical cables for spacecraft are similar to ordinary optical cables in structure, but there are some differences in material and technology due to the special environment such as extreme high-low temperature and space radiation.

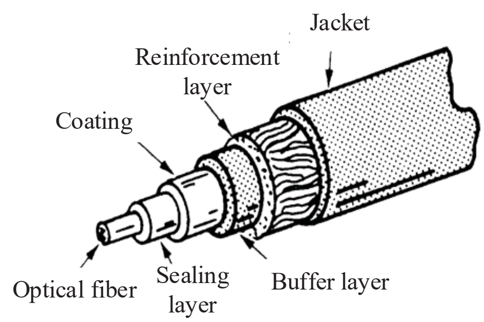

Figure 1. Structure of optical cable for spacecraft

In order to improve the overall performance of the optical cable, it is necessary to add a certain coating on the outside of the optical fiber. Coatings are generally polymer materials, which are used to enhance the flexibility, mechanical strength and aging resistance of optical fibers. At present, the coating of optical cables consists of two layers: the first layer has low modulus, which is closely bonded with the optical cladding, prevents the surface micro cracks from expanding, and reduces the micro-bending loss of optical fibers; the second layer has high modulus, which can improve the wear resistance and mechanical strength of optical cables. The coating material of optical cable for spacecraft should be able to withstand harsh high and low temperature environment, not easy to become brittle at low temperature and not easy to soften at high temperature. The reinforced layer and outer sheath are braided with silver-plated fiber structure, which can not only play an electromagnetic shielding role[2], but also improve the mechanical strength and flexural strength of optical cable[3]. In

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addition, the optical cables used in spacecraft should have good radiation resistance under the condition of guaranteeing transmission performance.

III. MAIN FAILURE MODES AND DEGRADATION MECHANISM

When optical cable is used outside the spacecraft cabin, it suffers the most severe space environment, which is mainly affected by extreme high-low temperature cycle and space radiation. Taking low Earth orbit spacecraft as an example, the highest surface temperature can reach 150℃ when the sun is directly irradiated, and the lowest temperature can be reduced to -150℃ when the sun is in the shadow, and a thermal cycle with a temperature difference of 300℃ will occur in about 90 minutes. Such a severe thermal cycle will make the cable material undergo repeated thermal stress, which will lead to thermal fatigue of the material under long-term action. In addition, space radiation is also an important factor causing the aging and failure of spacecraft optical cables. Under the irradiation of high-energy electrons, protons and gamma rays in space, the core will produce color centers[4-5], which will lead to the decline of optical transmission performance, thereby affecting the reliability and service life of optical cables[6]. The main failure modes of optical cables are shown in Table I.

TABLE I. MAIN FAILURE MODES OF OPTICAL CABLES

Structures		Functions	Failure Modes	Effect	Failure Causes	Failure Mechanisms	Types of Mechanisms	Stresses
Optical fiber	Optical fiber	Transmission optical signal	Fiber Fracture	Connection interruption	Expansion of Epoxy Resin	Excessive thermal stress	Overstress	Thermal shock
					Loss of epoxy resin	Excessive tension	Overstress	Pull
			Fiber Buckling	Increased optical loss	Epoxy resin hardening	Accumulation of axial pressure	Degeneration	Temperature drop
	Optical fiber end face	Transmission of signals between optical fibers through close contact	Optical Fiber Depression	Increased end clearance	Too much end-to-end relay	Excessive axial pressure	Overstress	Mechanical impact
					Mismatch of thermal expansion coefficient	Thermal stress fatigue	Degeneration	Temperature Cycle
			Optical fiber bulge	Scratch or even crush of optical fiber end face	Mismatch of thermal expansion coefficient	Thermal stress fatigue	Degeneration	Temperature Cycle
			Fiber End Damage	Signal Scattering	Particle invasion	Hard Particle Extrusion	Degeneration	Dust
					Moisture/pollutant intrusion	Corrosion	Degeneration	High humidity and salt fog
					Poor abrasion	Crack propagation	Degeneration	High humidity
	Coating	increase transmission performance	Thermal Weightlessness of Coating Materials	Increased optical loss	High temperature and radiation effects	Ageing	Degeneration	High temperature, radiation
Buffer layer		Cushioning stress	Necking	Strength reduction	Cold Drawing of Materials	Yield deformation	Overstress	Pull
			Crack	Connection interruption	Brittle fracture of materials	Poor toughness of materials	Overstress	Pull
Reinforcement layer		Increasing strength	Strength reduction	Strength reduction	High temperature and radiation effects	Deterioration	Degeneration	High temperature, radiation

IV. ACCELERATED DEGRADATION TESTING

Based on the analysis of failure modes of optical cables in spacecraft, the accelerated life test method of thermal cyclic stress is studied. Based on thermal fatigue mechanism, the accelerated test profile of fast temperature cyclic is designed. The comprehensive acceleration factor is designed by Arrhenius model of high temperature stress and Norris-Landzberg model of thermal cyclic stress, to determine the test time. Based on the accelerated test scheme, the temperature cycle accelerated life test is carried out, and the real test data are obtained for evaluating the life of optical cable.

Arrhenius model：

$$AF=\frac{\xi_{use}}{\xi_{test}}=\exp\left[\frac{Ea}{k}\left(\frac{1}{T_{use}}-\frac{1}{T_{test}}\right)\right] \tag{1}$$

AF is acceleration factor, Ea is the activation energy related to material (eV), the Boltzmann constant k=8.617×10^{-5}eV/K, and T is the absolute temperature.

Norris&Landzberg model：

$$AF=\frac{N_{use}}{N_{test}}=\left(\frac{\Delta T_{test}}{\Delta T_{use}}\right)^{B}\left(\frac{f_{use}}{f_{test}}\right)^{C}\exp\left[\frac{Ea}{k}\left(\frac{1}{T_{\max-use}}-\frac{1}{T_{\max-test}}\right)\right] \tag{2}$$

ΔT is temperature range, f is temperature change rate.

The test sample is 110m cables. In the process of cable test, the controlled quantity is temperature. The design of test condition is shown in Figure 2. The cable is tested cyclically according to the requirement of test profile. According to the formula (1) and (2), the acceleration factor of high temperature is 2.5, and the acceleration factor of the thermodynamic cycle is 113, then the total acceleration factor of the test profile is 282.5.

Pre-test stage:

(1) OTDR is used to test the optical cable before the test starts. The purpose is to select a smooth curve to bypass the step loss peak caused by the fusion point and micro-bending.

(2) Before testing, the residual stress of the cable should be released artificially. The cable should be wrapped in a 20 cm diameter ring and placed in a temperature shock chamber. The residual stress of the cable cladding should be released by baking at 80℃ for 30 min at constant temperature.

Test Beginning:

(1) Temperature shock chamber starts to run. The temperature change rate is accelerated from 25℃/min to 130℃. The temperature deviation is less than ± 2℃. The loss is measured at 130℃. When the change value is less than 2% within 1 minute, it is considered that the temperature of the optical cable is stable and the loss data are recorded. The loss data are maintained at 130℃ for 20 minutes.

(2) After keeping high temperature for 20 minutes, it enters the cooling process. The temperature varies from 130℃ to -100℃ at a rate of 20℃/min, and the loss is measured at -100℃. When the change value is less than 2% within one minute, the temperature is considered stable, and the data at - 100℃ is recorded for 40 minutes. 778 cycles were carried out in the temperature cycle test, totaling 1076 hours.

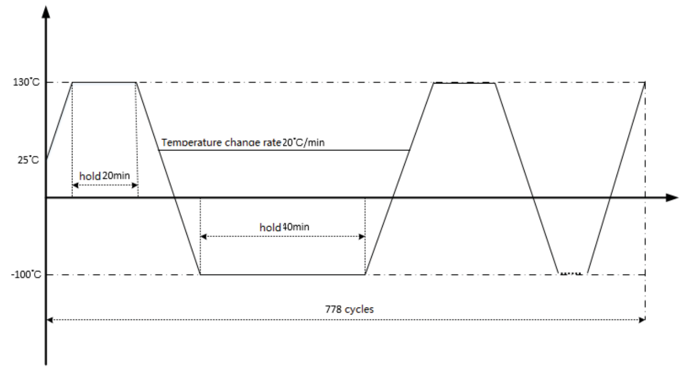

Figure 2. Temperature Cycle Accelerated Test Profile of Optical Cable

According to the temperature cyclic test, the temperature is strictly controlled, and the degradation data of the attenuation signal of the optical cable under each cycle number are obtained. Through linear fitting of degradation data, the linear fitting relationship of degradation data of optical cable under temperature cyclic stress can be obtained. The experimental results are shown in Figure 3. All data are measured at 1310nm wavelengths.

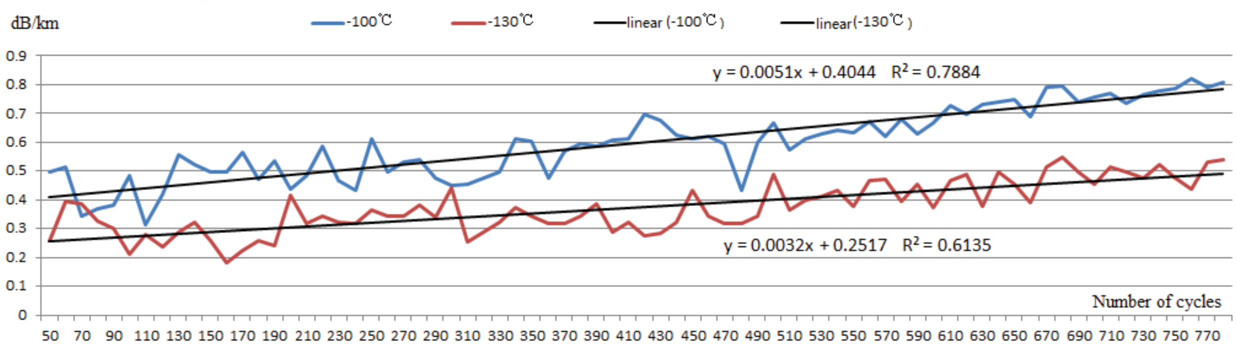

Figure 3. Performance degradation prediction of optical cable loss at 1310nm at high and low temperatures

From the test results, it can be seen that the thermal stress has a great influence on the degradation of the cable in the temperature cycling test, and the degradation curves under different stress are quite different. The degradation model of the experimental data is established to obtain the linear degradation law of the optical cable at high temperature and low temperature respectively. The root mean square error and the negative correlation coefficient of the fitting line are calculated with the example of low temperature - 100°C. As shown below, the RMSE and R^2 of optical cable can be obtained at 130°C.

$$\mathrm{RMSE} = \frac{1}{k\bar{y}}\sqrt{\sum_{i=1}^{k}(y_i-\hat{y}_i)^2} = 0.0583 \tag{3}$$

$$R^2 = 1-\frac{\sum_{i=1}^{k}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{k}(y_i-\bar{y})^2} = 0.1274 \tag{4}$$

The fitting parameters are shown in the table II and table III. Given a 95% confidence interval based on experience, the predicted values of cable performance degradation are drawn, as shown in Figure 4.

TABLE II. P1 PARAMETER VALUE OF DEGRADED MODEL

Temperature	Fitting value	95% confidence interval	SSE	R^2	RMSE
-100℃	5.12e-3	[3.36e-3,	0.15	0.1274	0.0583

		6.94e-3]			
130°C	3.25e-4	[2.85e-4, 5.86e-4]	0.2	0.4362	0.0672

TABLE III. P2 PARAMETER VALUE OF DEGRADED MODEL

Temperature	Fitting value	95% confidence interval	SSE	R^2	RMSE
-100°C	0.4074	[0.2365, 0.5162]	0.1496	0.1274	0.0583
130°C	0.2517	[0.1581, 0.3512]	0.199	0.4362	0.0672

It can be seen from the figure that the loss of optical cable is larger at low temperature and smaller at high temperature, but the 95% confidence interval is wider, which indicates that the fluctuation of optical cable loss is larger at high temperature.

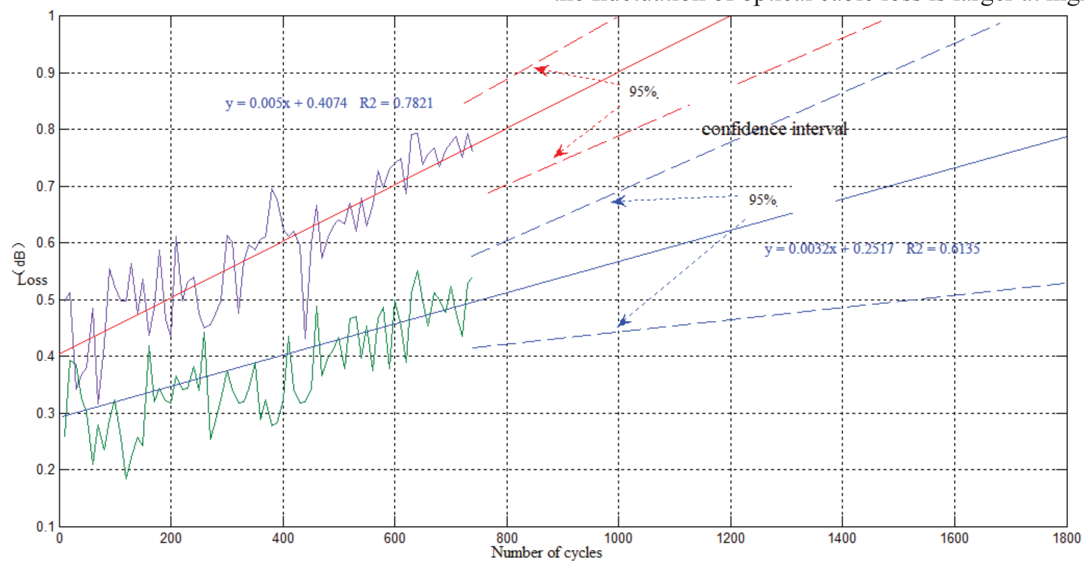

Figure 4. Performance degradation prediction of optical cable loss at 1310nm at high and low temperatures

V. LIFE PREDICTION OF OPTICAL CABLE BASED ON DEGRADED DATA

One solution is to use the state prediction method based on product performance degradation model[7]. The basic idea is to assume that the process of product performance degradation can be described by a state space model, that is, the state variable containing product performance degradation information and its performance degradation process. There is a corresponding relationship between them. By predicting the development of state variables in the future and combining with certain criteria, the performance degradation state and residual life of equipment can be predicted[8].

In recent years, the particle filter algorithm has theoretically solved the limitation of linear Gauss hypothesis for system description[9-10]. Therefore, the residual life prediction model of optical cable based on PF algorithm is selected in this paper.

The forecasting starting point is 400 cycles and the lifetime threshold is 0.8dB/km. The average lifetime of the predicted cable is 1050 cycles. The parameters of life distribution can be fitted according to the three-parameter Weibull distribution.

If the loss variable x obeys the three-parameter Weibull distribution, its probability density function is

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\mu}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{x-\mu}{\alpha}\right)\right]^{\beta} \tag{5}$$

The distribution function is:

$$F(x) = 1 - \exp\left[-\left(\frac{x-\mu}{\alpha}\right)\right]^{\beta} \tag{6}$$

Among them, β represents shape parameter, α represents scale parameter, and μ represents position parameter. The cable loss variable x obeys the three-parameter Weibull distribution and is recorded as $x\text{-}w\ (\alpha,\beta,\mu)$.

The shape parameter beta influences the shape change of distribution curve when the scale parameter alpha and position parameter mu of Weibull distribution are the same; when the shape parameter beta and position parameter mu of Weibull distribution are the same, the scale parameter alpha influences the size of abscissa scale; when the shape parameter beta and scale parameter alpha of Weibull distribution are the same, the position parameter is the same. Numbers of Mu determine the starting position of the curve. The life distribution parameters obtained by fitting are Weibull distribution, the distribution parameters are μ :727, α :69.7054, β :3.04795.

The predicted curve fitted is very close to the degradation law of the real transmission loss of optical cable. The 95% confidence interval can include almost all the real degradation data. As shown in the Figure 5.

In the same way, the service life is Weibull distribution, the distribution parameters are μ :1067, α :615.613 and β :4.45271 at 130℃. As shown in the Figure 6.

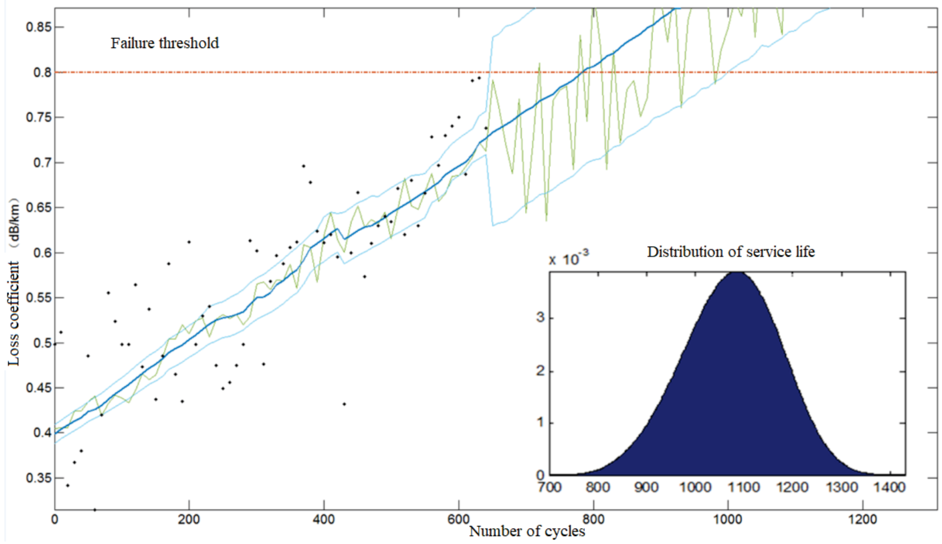

Figure 5. Life prediction of optical cables with Weibull distribution by particle filter method at 100°C

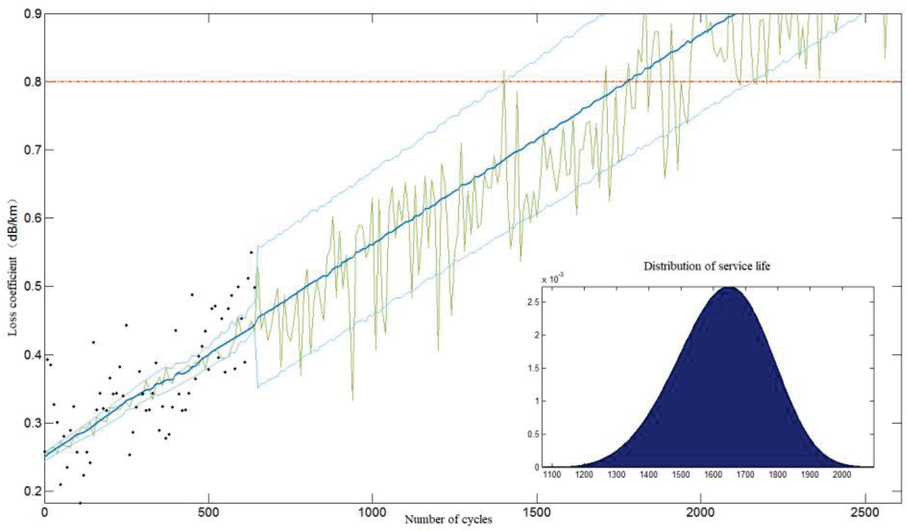

Figure 6. Life prediction of optical cable using particle filter method with Weibull distribution at 130°C

It takes 802 cycles to reach the failure threshold of 0.8dB/km at - 100℃, and 1750 cycles to reach the failure threshold at 130 ℃. Under the condition of temperature alternation, the failure prediction of optical cables should be carried out according to the temperature which first reaches the failure threshold. Therefore, the failure prediction should be carried out according to the temperature condition of - 100 ℃.

Based on the test data, the equivalent working life of the spacecraft extravehicular optical cable can be evaluated, and the test time can be converted to the equivalent time under normal conditions.

$$\hat{t}_{life} = AF * t_{test} = 282.5 \times 1109 = 313292\text{hours}=35\,years \quad (7)$$

The lower confidence limits of average life and failure rate under confidence level 0.95 are

$$\theta_L = \frac{\hat{t}_{\text{life}}}{\chi^2_{1-\alpha}(2)} = \frac{35}{\chi^2_{0.95}(2)} = 10.63\text{years} \quad (8)$$

$$\lambda_L = \frac{1}{\theta_L} = 1.07 \times 10^{-5} / \text{h} \quad (9)$$

VI. CONCLUSIONS

In this paper, based on performance degradation data, the performance degradation law of optical cable is studied, and a performance degradation-based life prediction method for optical cable of spacecraft is proposed. By establishing degradation model, the service life of optical cable is predicted.

(1) A modeling method for performance degradation of spacecraft optical cables is proposed. Based on the loss coefficient as a sensitive degradation parameter and

considering the test error, a performance degradation model of optical cables based on random effect is established, which clearly characterizes the performance degradation law of optical cables under accelerated stress conditions.

(2) Based on the degradation model of optical cable performance, a life prediction method of particle filter is proposed. It is predicted that 802 temperature cycles are needed when the loss coefficient of optical cable reaches the failure threshold of 0.8dB/km, and the average life is 10.63 years under the confidence of 0.95.

References

[1] HUANG X. D., WANG Y., SUN Y. Y., et al, "Mechanism analysis on the impact of coating to fiber Bragg grating strain transfer," Chinese Journal of Scientific Instrument.2016, 37(6), pp. 1233-1240.

[2] Gao Xiaotian, "Preparation and Performance Research of Radiation-resistant Fabric Interweaved with Silver-plated Fiber," Southwest University of Science and Technology Master Degree Thesis, 2017.

[3] Feng Bo, "Study of Stripping Optical Fiber Coating Using CO_2 Laser," Wuhan University of Technology Master Degree Thesis, 2014.

[4] WANG X. Q., ZHANG C. X., JIN J., et al, "Radiation-induced attenuation effect on special optical fibers applied in space," Infrared and Laser Engineering, 2011, 40(12), pp. 2516-2520.

[5] LIU F H, AN Y Y, WANG P, et al, "Radiation-induced loss of pulsed γ-ray on optical fibers,". Infrared and Laser Engineering, 2013, 42 (4), pp.1056-1062.

[6] JIA X., ZHU H. J., ZHANG H. Q., et al, "Space radiation applicability of pure silicon-core optical fibers," Infrared and Laser Engineering, 2017, 46(8), pp. 1-5.

[7] Wang W, Hussin B, "Journal of the Operational Research Society", 2009, pp.60-89.

[8] Ray A, Tangirala S, "IEEE Transactions on Control Systems Technology," 2006, 4(4), pp.443.

[9] Willett P K, Kirubarajan T, "Proceedings of SPIE", Orlando: SPIE, 2002.

[10] SUN Lei, JIA Yun xian, CAI Liying, LIN Guoyu, ZHAO Jinsong, "Research on Engine Remaining Useful Life prediction Based on Oil Spectrum Analysis and Particle Filtering," Spectroscopy and Spectral Analysis, 2013,33(9), pp.2478-2482.