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Life Prediction of Naval Gun Barrel Based on Multi-source Information Fusion

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Abstract. The performance of naval gun barrel highly influences the operational lifespan. During the firing process, it is a quite challenge to predict the life of the naval gun due to many unknown factors in the complex physical and chemical reactions that occur in the barrel inner surface. This paper presents an optimized life prediction model which considers the information difference of ablative and fatigue life.The model consists of three modules, heat transfer simulation model, fatigue finite element model, and data fusion based on D-S evidence theory. The heat transfer simulation model and fatigue finite element model are established by simulating the firing process of a naval gun, and the life distribution is calculated. On this basis, a life prediction model is improved taking into account the variability of erosion and fatigue life data. The result shows that the established model can predict the life of the barrel more accurately and correctly judge the state of the body tube and improve the reliability of the naval gun.

Keywords: life prediction, mechanical reliability, D-S evidence theory, naval gun barre

1. Introduction

The barrel is a structural component that holds the shell and withstands the force of the gunpowder gas during the gunpowder firing process. With the firing of gunpowder, a series of complex and comprehensive physical and chemical reactions occur between the barrel, the gas and the belt, such as heat transfer, diffusion, phase change, corrosion and fatigue, which cause damage to the inner wall of the body barrel. According to the type of damage, the body tube life can be divided into erosion life and fatigue life.When the damage reaches a certain degree, the life of the barrel ends and the barrel must be replaced. Otherwise, inaccurate firing, stoppage of fire or even safety accidents due to blowing up of the bore may occur.Therefore, The fatigue life of the barrel is greater than the service life, and the service life is predicted by the erosion life, which may be inaccurate in relation to the actual service life, so it is important to ensure maximum shooting within the actual service life of the barrel.

The study of barrel life is mainly divided into two categories: erosion and fatigue. the study on erosion mainly includes thermochemical mechanism, internal ballistic, and thermal coupling. Ahmad only considered the effect of erosion on mechanical properties, which did not become a systematic theory [1]. Sopok et al others studied the comprehensive effect of thermochemical and mechanical on body tube, and established a model of thermochemical and mechanical wear mechanism [2]. Xiaolong Li established a critical isothermal model based on three stages of thermochemical reactions: slow erosion stage, thermal-chemical erosion stage, and melting erosion stage, and used numerical numerical simulations were used to calculate the maximum erosion of the barrel to predict the lifespan [3].

The main focus for the mechanical influence of barrel is on fatigue life. Initial cracking is an important factor affecting fatigue life. In view of the uncertainty of initial crack size, F. Proschan established a probabilistic model of initial crack size and verified that the body tube life distribution is a mixture of the moving Weibull distribution of the common shape parameter [4]. Audino considered the influence of residual stress on fatigue life on the basis of the effect of initial cracking on life [5]. ohn H. Underwood further considered material strength, initial crack size and Bauschinger modified self-reinforced residual stresses to establish fatigue life model [6]. Due to the influence of thermal-chemical and fatigue factors, the combination of both thermochemistry and fatigue has been increasingly studied. Liqun Wang combined

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friction with thermochemistry and established a barrel degradation model considering the thermochemical reaction of frictional heat generation [7].

More studies of barrel life consider erosion or fatigue life separately, but the damage caused by erosion and fatigue is different. The method of evaluating tube life by one of the fault mechanisms has some limitations. In view of the core factors of barrel life, considering the difference in information between fatigue and erosion life, and then uses a multi-source fusion method to integrate the fatigue and erosion information to find the barrel lifespan.

2. Existing methods

2.1. Erosion life prediction model

The evaluation standard of barrel life is: judging its life from the range, shooting accuracy, projectile power and other aspects. When the naval gun fails to meet the tactical requirements, its life will be terminated. This establishes the end-of-life criteria for ablative life as follows.

(a) The percentage reduction in muzzle velocity exceeds the value specified for the gun type (5%-10%).

(b) The shooting intensity exceeds the prescribed range.

(c) The amount of erosion wear at the beginning of the rifling exceeds a specified value.

(d) Rifling pressure drops so that 30% of projectiles cannot be released from the fuse safety or cause continuous blind firing, etc.

(e) The belt is shredded or there is a horizontal bomb, near bomb, early explosion, etc.

$$\omega = Ae^{BT_{\max}} \tag{1}$$

$$T_{\max} = 1.906 \times \frac{\left(T_f - T_c - 600\right)\sqrt{\omega}}{d} \tag{2}$$

$$W = \sum_{n=1}^{N} Ae^{BT_{\max}} \tag{3}$$

Equation (1), (2)and (3) is the commonly used single shot erosion life model. ω is the charge quantity; A and B is an empirical constant,which are related to the inner wall materials of the barrel and the nature of the gunpowder. T_f is the detonation temperature of propellant; is the corrected value of the temperature when the additive is present. The amount of erosion during continuous firing is considered to be directly cumulative.

Therefore, this paper first calculates the change of gunpowder gas temperature inside the body tube, then determines the change curve of convective heat transfer coefficient, and then ABAQUS was used to establish the heat transfer simulation model to determine the change of temperature of the inner wall of the barrel.

Table 1: Barrel parameter

Naval gun barrel parameters			
Name	**Numerical value**	**Name**	**Numerical value**
Cross sectional area of bore（dm^2）	1.394	Ammunition weight（kg）	33.4
The volume of the powder chamber（dm^3）	8818.58	Barrel trip（dm）	65
starting pressure（KPa）	3070000	Coefficient of minor work	1.152
Coefficient of motion resistance	1.03	Thermal coefficient of gunpowder	0.2
gunpowder impetus（kg·dm/kg）	8.7657e5	residual volume（dm^3/kg）	1
Gunpowder density (kg/dm^3)	1.6	charge mass (kg)	10.5
Coefficient of burning rate of gunpowder (dm^3/(s·kg))	7.7525e-4	pressure exponent	0.82
thick（m）	0.00081	Gunpowder inside diameter（m）	0.00079

According to Table 1 and internal ballistics, the change data of pressure and velocity in internal ballistics and after effect period are obtained. Then the gas density during the internal ballistic period can be calculated from equation (4), (5) and (6). Fig. 1 shows the change in density during the internal ballistic period, reaching 5.245×10^5 kg/m3 at 1.0782ms.

$$\rho = \frac{\omega\psi}{Sl + W_0 - \frac{W_0(1-\psi)}{\Delta} - \omega\psi\alpha} \tag{4}$$

$$\psi = \begin{cases} \chi z(1+z+\mu z^2) & z<1 \\ 1 & z>1 \end{cases} \tag{5}$$

$$\frac{dz}{dt} = \begin{cases} \frac{\mu}{e_1} p^{0.84} & z<1 \\ 0 & z>1 \end{cases} \tag{6}$$

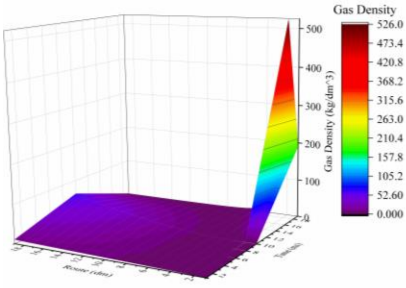


Fig. 1: Gas density as a function of time, as a function of travel

1) Internal and external boundary conditions

The body tube heat transfer is mainly divided into axial and radial. Since the body tube temperature changes along the radial direction about one thousand times as much as the axial direction, the radial heat transfer is mainly considered in the heat transfer process [8]. If the friction between ammunition and barrel and radiation heat transfer are ignored, and the neglected radiation heat transfer is compensated by expanding convective heat transfer coefficient, the heat transfer of barrel can be simplified to one-dimensional heat transfer, and the relation is expressed in equation .

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \quad r_0 \le r \le R, t \ge 0 \tag{7}$$

where T is the temperature of the inner wall of the barrel; t is time; r is the distance of a point in the barrel from the inner surface; α is the temperature conductivity coefficient of the barrel material.

It is assumed that there is only convection heat transfer between the gunpowder gas and the inner wall of the barrel, and the interior of the barrel is a heat transfer between materials. Equation (8) is established on the basis of equation (7) to compensate for radiative heat transfer by correcting the forced convective heat transfer coefficient of the gunpowder gas as a boundary condition for the thermal convective heat transfer coefficient.

$$h(z,t)[T_g(t) - T(t)] = -\lambda \frac{\partial T}{r\alpha} \tag{8}$$

where T_g is the function of the temperature change of gunpowder gas in the bore with time, which can be obtained from the internal ballistic calculations; h is the forced convective heat transfer coefficient of the gunpowder gas.

Ignoring the conditions such as the heat transfer between the gas entrained solid particles on the inner chamber of the barrel, the gas heat transfer state is appropriately simplified：

$$h = C_v w_r \rho = \alpha_0 \rho \tag{9}$$

where C_v is the specific heat of constant volume of gunpowder gas; w_r is the average radial impact velocity of the gunpowder gas on the bore of the body tube. The values in the gun range from 0.21 to 0.42, and is 0.3

in this paper. Then the convective heat transfer coefficient of gunpowder gas from the inner bore and the inner bore can be calculated. Fig. 2 shows the relationship between the convective heat transfer coefficient and time and route.

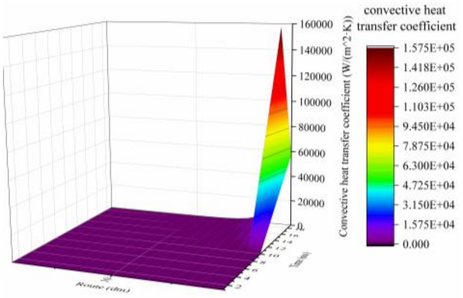


Fig. 2: Gas density as a function of time, as a function of travel

2) External boundary conditions

The heat exchange process also exists between the outer wall and the environment. The outer wall of the tube is ignored to dissipate heat in the form of heat radiation, and only the effect of natural convection between the outer wall of the tube and the air is considered. For natural convection heat transfer, the flow state of the fluid (ideal gas) is judged by using the Graschow number, which is defined as equation (10):

$$G_r = \frac{gD^3(T_F - T_\infty)}{{v_0}^2 T_\infty} \tag{10}$$

where D is the outer diameter of the barrel, T_F is the qualitative temperature of the outer wall of the body tube; T is the initial temperature of the outer wall of the barrel, T takes the value of 293K; v_0 is the viscosity of the air at the qualitative temperature and takes the value of 640.1110.

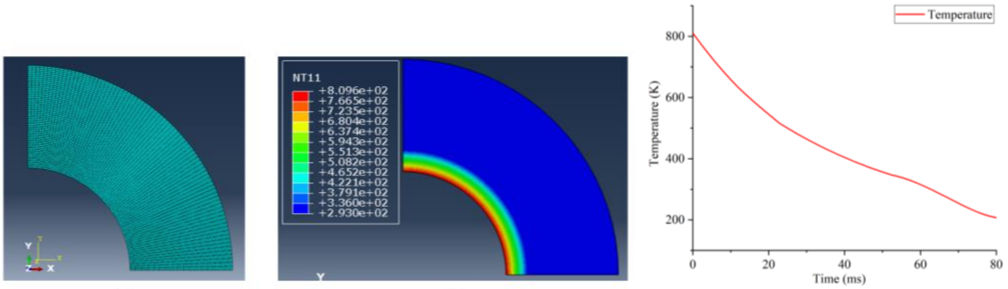
The convection coefficient between the outer wall of the origin pipe and the environment is calculated by $h = \frac{N_M \lambda}{d}$,which is 11.5KW/($m^2$·K).

3) Body tube heat transfer simulation

The heat transfer coefficient was taken as the boundary condition, the temperature change during shooting was taken as the input, and the inner wall temperature of the barrel was taken as the output. Combined with the barrel material characteristics provided by Table 2 a heat transfer simulation model as shown in Fig. 3 is built using ABAQUS.

Table 2: Thermal ConductivityAnd Specific Heat

Temperature（K）	**Thermal conductivit（W/(m·°C)）**	**Specific heat （J/(kg·°C)）**
293	50	523
373	46.05	540
473	43.97	553
573	41.87	578
673	939.77	611
773	37.68	674
873	36.68	754
973	33.06	849
1073	29.06	946



(a) (b) (c)

Fig. 3: Heat transfer simulation modelling (a), results (b), temperature change (c).

Combining equation (3) with the simulated temperature of the tubes, Fig. 3(c) shows the temperature variation at the inner surface, which has a maximum temperature of 809.56K. The erosion life of the barrel can be calculated to be 2888 rounds. As the ambient temperature varies randomly, Latin hypercube is used to sample the maximum temperature. And the barrel erosion life follows a logarithmic distribution. The formula is as follows:

$$f(t)=\frac{1}{0.13392t\sqrt{2\pi}}-e^{-\frac{1}{2}\left(\frac{\ln t-7.96864}{0.13392}\right)^{2}} \qquad t>0 \tag{11}$$

2.2. Fatigue life prediction odels

The fatigue damage of the naval gun barrel is characterised by the following:

(a) After the gun has fired a dozen or a few rounds of ammunition, a large number of network cracks will occur inner wall of the barrel, which is negligible compared to the crack expansion time, so the fatigue life of the barrel is mainly the time of crack expansion [10].

(b) The self-tightening body tube has a slower crack expansion compared to the normal body tube, and the self-tightening body tube can significantly improve the body tube life.

(c) Temperature has a certain influence on crack propagation, the crack expansion distance will be reduced when the temperature increases.

The naval gun is low circumferential fatigue, and according to the relationship between fatigue life and cyclic stress (equation (15)), the relationship between fatigue life and projectile number can be deduced (equation(16)).

$$\frac{da}{dN}=C\left(\triangle K\right)^{m} \tag{12}$$

$$N_{p}=\left[\frac{1}{a_{0}^{\frac{m}{2}-1}-a_{i}^{\frac{m}{2}-1}}\right]\frac{2}{C\left(m-2\right)\left(F\triangle\sigma_{\theta}\right)^{m}} \tag{13}$$

where N_p is the number of projectiles fired from naval gun; a_0 is the initial crack size; a_i is the crack expansion size; F is the dimensional parameter.

When the crack size is greater than or equal to the critical crack size, the barrel will fracture and fail. And the critical crack size is influenced by the magnitude of the shear stress.

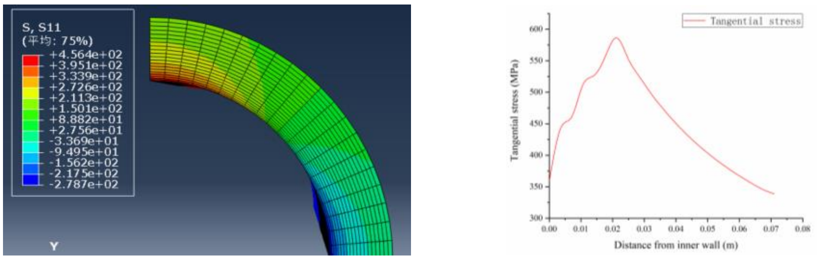
$$a_{c}=\frac{K_{JC}}{\pi\left(F\triangle\sigma_{\theta}\right)^{2}} \tag{14}$$

where K_{JC} is the material strain fracture toughness of the material; $\triangle\sigma_{\theta}$ is the shear stress amplitude.

Table 2: Thermal conductivity and specific heat

Name	**Numerical value**
Density（kg/m^3）	7081
Elasticity modulus（MPa）	2.301×10^{5}
poisson's ration	0.3

Based on the parameters in Table 3 the pressure subjected to 375MPa was taken as the input and the inner wall shear stress as the output, and ABAQUS was used to simulate the self-tightening barrel.



(a) (b)

Fig. 4: Radial variation of tangential stress.

Fig. 4 shows the variation of the tangential stresses in the inner wall along the radius, when the inner wall is subjected to the ammunition pressure. The distribution is not uniform because the barrel is 30% self-tightening and the residual stresses in the inner wall change the force distribution. The maximum tangential stress of 586.25MPa is reached at 21.3mm from the surface, with the life of 3951 rounds. As the material fracture toughness, material constants and dimensional parameters are related to the material properties, the fatigue life distribution of the body tube was obtained by considering the uncertainty of the parameters using Latin hypercube sampling.

$$f\left(t\right)=\frac{1}{0.1514t\sqrt{2\pi}}-e^{-\frac{1}{2}\left(\frac{\ln t-8.0528}{0.1514}\right)^{2}}\qquad t>0 \tag{15}$$

3. Lifetime prediction models based on data fusion

D-S evidence theory is a method for dealing with multi-source data, which is a generalization of Bayesian methods that can effectively and flexibly deal with uncertain information without using prior distributions. And it can effectively solve the problems of ambiguity, uncertainty and conflict between information. D-S evidence theory can assign probabilities to sets consisting of multiple types of information through certain principles subsets as uncertainty [11].

The information entropy and J-S scatter are used to find the information difference between erosion life and fatigue life, and then their information difference is used for data fusion to predict the barrel life [12].

Information entropy is a method used to deal with uncertain information. Assuming that A_i is an event that is uncertain information and $\left|A_i\right|$ represents the number of elements contained in the event A_i, then the equation for the entropy of the set information is:

$$E_d=-\sum_{A\subseteq\Theta}m\left(A_i\right)\lg\frac{m\left(A_i\right)}{2^{\left|A_i\right|}-1} \tag{16}$$

The J-S divergence is a measure of the similarity of two or more probability distributions, but the it does not require the probability distribution to be continuous.

If X is random variable. $\left\{m_{21},m_{22},m_{23},\cdots,m_{2n},\right\}$ and $\left\{m_{11},m_{12},m_{13},\cdots,m_{1n},\right\}$ are two forms of probability distributions, then the divergence between m_1 and m_2 is:

$$JS\left(m_1,m_2\right)=E_d\left(\frac{m_1+m_2}{2}\right)-\frac{1}{2}E_d\left(m_1\right)-\frac{1}{2}E_d\left(m_2\right) \tag{17}$$

The degree of variation between messages is further established on the basis of information entropy and divergence.

$$DMM=\begin{bmatrix}1 & \cdots & 1/d_{1n}\\ \vdots & \cdots & \vdots\\ 1/d_{n1} & \cdots & 1\end{bmatrix} \tag{18}$$

$$ED\left(m_i\right)=\sum_{j=1,j\neq i}^{n}D_{ij} \tag{19}$$

The steps in the fusion of erosion life and fatigue life on this basis are:

(a) The evidence obtained is assigned a basic probability, while the evidence is to be expressed in the form of a basic information distribution function.

(b) Calculate the collective information entropy E_{di} of the event A_i according to the information entropy equation (16).

(c) Calculate the difference d_{ij} between various evidences to prevent the allocation of zero weight to some evidences, resulting in large error of results. Then, according to the difference d_{ij} between evidences, list the difference measurement matrix *DMM*, and then calculate the difference degree $ED(m_i)$ between various evidences according to the *DMM*.

(d) Based on equation (19), the J-S divergence measure matrix JDM is listed according to each divergence, and the average divergence of each evidence of the J-S divergence measure matrix is also calculated, and then the evidence credibility $Cd(m_i)$ is calculated according to the average divergence.

$$\overline{JS} = \frac{\sum_{j=1, j\neq i}^{n} JS_{ij}}{n-1} \tag{20}$$

$$S_d\left(m_i\right) = \frac{1}{\overline{JS}} \tag{21}$$

$$C_d\left(m_i\right) = \frac{S_d\left(m_i\right)}{\sum_{i=1}^{k} S_d\left(m_i\right)} \quad 1 \leq i \leq n \tag{22}$$

(e) The evidence credibility $Cd(m_i)$ can be adjusted and optimised to some extent, and the result of the adjustment and optimisation is the amount of evidence difference, and then the weight of each piece of evidence is calculated according to the amount of evidence difference, then each piece of evidence gets a new weight, and on this basis the D-S rule is applied to fusion, and the number of fusion is (n-1) times.

The parameter distribution of erosion life and fatigue life can reflect the barrel life characteristics. They are the core factors that affect the life, and the barrel lifespan model is simplified and other factors are ignored. Through its parameters to calculate the variability between the erosion life and fatigue life, and fusion, to obtain a unified mean and variance, that is the barrel life prediction model.

Before the information discrepancy can be solved, a fuzzy evaluation of the erosion and fatigue life needs to be carried out by the expert evaluation method to establish the affiliation function and determine its basic probability assignment.

Table 4: Lifetime Distribution Parameters

	Average	**Standard deviation**
Erosion life distribution	7.96864	0.13392
Fatigue life distribution	8.0528	0.1514

Table 5: Lifetime Distribution Parameters

	A1	**A2**	**∅**
μ1	0.684	0	0.316
μ2	0	0.472	0.528
σ1	0.369	0	0.631
σ2	0	0.2867	0.7133

According to D-S theory evidence, the conflict factor between parameters can be calculated：

$$H_1 = \sum_{X \cap Y = \varnothing, \forall X, Y \subseteq \Theta} m_i\left(X\right) \times m_j\left(Y\right) = 0.684 \times 0.472 = 0.3228 \tag{23}$$

$$H_2 = \sum_{X \cap Y = \varnothing, \forall X, Y \subseteq \Theta} m_i\left(X\right) \times m_j\left(Y\right) = 0.369 \times 0.2867 = 0.1058 \tag{24}$$

Then it can be verified that the information between erosion and fatigue is somewhat conflicting and the underlying probability distribution of the mean and standard deviation can be derived.

The degree of variation is：

$$ED(\mu_1) = 2.7992,\ ED(\mu_2) = 3.0183$$

$$ED(\sigma_1) = 3.0140,\ ED(\sigma_2) = 2.8967$$

The life prediction model finally obtained by D-S evidence theory is：

$$f(t) = \frac{1}{0.1434t\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln t - 7.9769}{0.1434}\right)^2} \quad t > 0$$

Table 6: TABLE VI. Error Assessment

	Lifespan	**error**
Eriosion life model	2888	3.7%
fatigue life model	3951	31.7%
Information differential life model	2913	2.9%

Table 6 shows the error between the three models and the actual service life (3000 rounds). The relative error between the erosion life and fatigue life is 26%, which verifies that the erosion has a great influence on the tube life. The error in the single life prediction model shows the interaction between both erosion and fatigue, and the error of the proposed life model considering the information difference is reduced to 2.9%, proving the validity of this model.

4. Conclusion

Based on the fact that fatigue and erosion are the main factors influencing the life of the barrel, heat transfer simulation model and fatigue model are established to predict the erosion life and fatigue life of the body barrel. The relationship between erosion and fatigue has a certain influence on barrel life, so the difference between them is considered through information entropy and divergence, and the barrel life prediction model is established, which is based on the data fusion. The model error was reduced from 3.7% to 2.9% after comparing the established life prediction model with the actual body tube life.

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