Fatigue Simulation Analysis of Semi-open Thick-walled Cylinder under Cyclic Loading

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Abstract. The fatigue of the gun barrel is an important factor affecting the life of the gun barrel. The gun barrel is simplified into a semi-open thick-walled cylindrical container. The stress form and load type are analyzed according to the internal ballistic model of the artillery. The model is set to simulate the initial boundary conditions and load parameters, and the fatigue response of the gun barrel under different cyclic load impacts is compared and analyzed. The results show that the fatigue danger zones of the different load strengths are basically the same, and the load strength has the fatigue life of the gun barrel. The greater the impact, the life of the body under the strong charge load is reduced by 59.81% compared with the life of the positive charge. In the design and test of the gun barrel, the life of the body under the strongest load is used as the evaluation standard.

1. Introduction
The muzzle velocity, bore pressure and range of gun in the process of firing are directly reflected in the force amplitude of barrel, and the firing speed of gun is reflected in the alternating frequency of force. Both of them have important effects on the fatigue of barrel. Barrel fatigue is the behavior of crack propagation in barrel at each launch. It is an inherent property of barrel material. With the expansion and improper maintenance of crack, barrel is prone to dangerous accidents such as chamber expansion and even chamber explosion [1-3].

The fatigue mechanism and fatigue life of barrel have been studied by domestic and foreign scholars. Gu Jingui[4][5] made a comprehensive analysis of the literature on the fatigue problem of foreign gun barrels. The mechanical behavior of thick-walled cylinder under the action of annular temperature field is analyzed, and the reliability of thick-walled cylinder under internal pressure and thermal load is systematically studied by Liu Xinsheing and Xu Bingye[6][7]. We take a certain type of the gun barrel as the research object, which is simplified to a thick-walled cylinder pressure vessel. The stress and strain of the thick-walled cylinder under semi-open condition are analyzed. The loads are analyzed according to the pressure in the bore obtained from the interior ballistic equation, and then the mechanical fatigue of the thick-walled cylinder is being simulated.

2. Basic Hypothesis and Physical Model
Thick-walled cylinder vessel is a special type of pressure vessel under cyclic load. As far as the working state of artillery is concerned, the number of cyclic loads the barrel can bear is the key index of its life.

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2.1. Basic Hypothesis
We take the thick wall shape as ideal cylindrical shape, thick wall material is homogeneous and isotropic, thick wall cylinder withstand pressure \( p_e \) perpendicular to the surface of the cylinder wall and evenly distributed. Through the above assumptions, the stress problem of the thick-walled cylinder can be simplified to the cylindrical axis symmetry problem under the static force, and the theoretical force and deformation of the thick-walled cylinder can be calculated.

![Figure 1. Schematic diagram of thick-walled cylinder.]

As shown in Fig. 1, \( r_1 \) is inner radius of thick-walled cylinder, \( r_2 \) is outer radius of thick-walled cylinder, \( P_1 \) is internal pressure, \( P_2 \) is external pressure. As shown in Fig. 2, The Cartesian coordinate system is taken on the unit body. The origin \( O \) is located at the center of the bisector plane unit of the dihedral angle \( d\theta \).

![Figure 2. Diagram of Force Analysis for Cylindrical High Pressure Vessel.]

2.2. Stress Model
According to the force analysis of thick-walled cylinders, it is necessary to determine the stress and strain in three directions. According to the static equilibrium condition and the geometric relationship of the thick-walled cylinder deformation, and using the boundary conditions, the stress and strain formula can be obtained.

According to the static balance, we know \( \sum X = 0 \), then can obtain

\[
\left( \sigma_r + d\sigma_r \right) (r + dr) d\theta dz - \sigma_r \bullet r d\theta dz - 2\sigma_z \sin \frac{d\theta}{2} d_r dz = 0
\]

By \( \sum Z = 0 \) we can get

\[
(\sigma_z + d\sigma_z) r dr d\theta - \sigma_z \bullet r dr d\theta = 0 \quad \text{(1)}
\]

According to equation(1), we can know \( \sigma_z \) is constant. We do not have to list it because of can’t get an independent equation by \( \sum Y = 0 \), \( \sum M = 0 \). For a single thick-walled cylinder, the external pressure and the axial stress are constant, so the stress equations are obtained by solving the above equations together.
\begin{equation}
\sigma_z = p_1 \frac{r_2^2 - r_1^2}{r} - p_2 \frac{r_1^2 - r_1^2}{r}
\end{equation}

\begin{equation}
\sigma_r = p_1 \frac{r_2^2}{r} + r_2^2 - p_2 \frac{r_2^2}{r} + r_1^2
\end{equation}

\begin{equation}
\sigma_z \text{ is cons tan t}
\end{equation}

Then we can get strain equation (3),

\begin{align*}
\varepsilon_r &= \frac{1}{E} \left( p_1 \frac{r_1^2 (1+\mu) r_1^2 - (1-\mu) r_2^2}{r_2^2 - r_1^2} - p_2 \frac{r_1^2 (1-\mu) r_1^2 + (1+\mu) r_2^2}{r_2^2 - r_1^2} - \mu \sigma_z \right) \\
\varepsilon_z &= \frac{1}{E} \left( p_1 \frac{r_1^2 (1+\mu) r_1^2 - (1-\mu) r_2^2}{r_2^2 - r_1^2} - p_2 \frac{r_1^2 (1-\mu) r_1^2 + (1+\mu) r_2^2}{r_2^2 - r_1^2} - \mu \sigma_z \right) \\
\varepsilon_z &= \frac{1}{E} \left( -2 \mu \frac{p_1 r_1^2}{r_2^2 - r_1^2} + \sigma_z \right)
\end{align*}

It can be concluded that the stress and strain in three directions at any point can be obtained when the inner and outer diameter of the thick-walled cylinder and the compressive load \( p_1 \) (the average pressure in the barrel during shooting) are known.

3. Constitutive equation of body fatigue

3.1. Gun barrel load analysis

According to the basic hypothesis of classical interior ballistics, the equations for calculating interior ballistics show that the pressure distribution law of projectile in the bore is as follows during the movement period of projectile in the bore.

Bore pressure \( p_t \) > Pressure at any interface in bore \( p_x \) > Projectile bottom pressure \( p_d \). Then we can obtain (4).

\begin{equation}
p_x = p_d \left[ 1 + \frac{\omega}{2\phi m} \left( 1 - \frac{x^2}{L} \right) \right]
\end{equation}

\( L \) is distance from the bottom of the chamber to the bottom of the projectile, \( x \) is distance from cross section to bottom of chamber, \( m \) is charge quality, \( q \) is projectile mass, \( \phi \) is Secondary Work Coefficient considering Friction and Projectile Rotation. The relationship among average pressure, bottom pressure and bottom pressure can be obtained by simplified calculation,

\begin{equation}
p = p_d \left( 1 + \lambda_1 \frac{\omega}{\phi m} \right)
\end{equation}

\begin{equation}
p_t = \left( 1 + \lambda_1 \frac{\omega}{\phi m} \right) \left( 1 + \lambda_2 \frac{\omega}{\phi m} \right) p
\end{equation}

According to the relationship between bottom pressure and average pressure, the maximum bottom pressure \( p_{\text{max}} \) can be calculated.

\begin{equation}
p_{\text{max}} = \left( 1 + \lambda_1 \frac{\omega}{\phi m} \right) \left( \frac{\omega}{\phi} \right) p_{\text{max}}
\end{equation}

The interior ballistic equations of a certain type of artillery are programmed with MATLAB, and the pressure in bore is simulated under different charge conditions. The maximum pressure in bore is
314.35 MPa under the condition of strong charge and 285.35 MPa under the condition of positive charge.

Figure 3. t-p Curve under Positive Charge.

Figure 4. t-p Curve under Strong Charge.

3.2. Constitutive equation of barrel fatigue
The purpose of fatigue research on thick-walled cylinder is to further analyze the fatigue life of barrel by studying the fatigue crack propagation mechanism of thick-walled cylinder under cyclic loading.

The characteristics of mode I crack are that the external load is perpendicular to the crack surface and the displacement of the crack surface is perpendicular to the crack surface; mode II crack is characterized by the relative slip of the crack surface along the x direction in its plane; mode III crack is the corresponding anti-plane crack, and the relative slip of the crack along the z direction.

We can obtain the stress component and displacement component at R near the crack tip of mode I crack.

\[
\begin{align*}
\sigma_{11}(r, \theta) &= \frac{K_1}{\sqrt{2 \pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3 \theta}{2}\right) \\
\sigma_{22}(r, \theta) &= \frac{K_1}{\sqrt{2 \pi r}} \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \sin \frac{3 \theta}{2}\right) \\
\sigma_{12}(r, \theta) &= \frac{K_1}{\sqrt{2 \pi r}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3 \theta}{2}
\end{align*}
\]
\( K \) is stress intensity factor, \( E \) is shear modulus and \( v \) is Poisson's ratio.

4. Simulation and Calculation

4.1. 3D Modeling

Taking a certain type of gun barrel as the analysis object, the finite element model is established based on the relevant data, and the preliminary model is established by using ANSYS. The material is 30CrNi2MoVE gun steel, whose elastic modulus is 2.04e11N/M2, Poisson's ratio is 0.286, density is 7.86e3Kg/M3, shear modulus is 7.94e10N/M2, tension strength is 1.15e9N/M2, and yield strength is 8.35e8N/M2.

4.2. Calculation

In the mesh generation, the software was used to optimize the mesh generation. A total of 6536 nodes and 1008 cells were obtained. As shown in the figure below. According to the calculation of internal ballistics, different loads are applied under different loads of different charges, and the transverse stress load 510E6Pa is applied on the inner surface of the cylinder high pressure vessel with a cyclic frequency of 0.6Hz.

4.3. Results and analysis

Equivalent stress (Fig. 7) and equivalent strain (Fig. 8) of each element of cylindrical high pressure vessel under load are obtained by simulation calculation.

After simulation calculation, the stress, strain, cyclic load equivalent stress and fatigue sensitivity change of the cylinder high pressure vessel under the set load can be obtained as shown in the following figure.
According to the simulation data, the maximum load of the cylinder high-pressure vessel is 1.1493E5 times. When the number of cyclic loads exceeds, the cylinder high-pressure vessel is fatigue-fractured. During the cyclic action, the minimum equivalent strain time is Smin=26492Pa, Smax =7.79477E5Pa; at the maximum strain time, Smin=6.611E7Pa, Smax=1.9853E9Pa. During the cyclic action, the maximum strain is 8.3674E-4m and the minimum strain is 3.9749E-4m. It can be seen from the stress cloud diagram that during the cyclic loading process, the stress and strain in the front and the tail of the cylindrical high-pressure vessel are concentrated, and the middle portion of the cylindrical high-pressure vessel is more likely to be fatigued.

![Figure 11. Banner load and equivalent stress correction theory.](image1)

![Figure 12. Fatigue sensitivity change.](image2)

5. conclusion
We take a certain type gun barrel as the research object which is simplified into a thick-walled cylindrical container. The classical internal ballistic model is used to model the load of the thick-walled cylinder, and the elastoplastic stress analysis of the thick-walled cylinder is carried out. The fatigue simulation model of thick-walled cylinder was established. The stress and strain of the thick-walled cylinder under different load impacts and the fatigue properties of the material were simulated by finite element software. The fatigue of thick-walled cylinder under different cyclic load impacts was obtained. The simulation results show that different load strengths have a great influence on the fatigue life of the body tube. Therefore, in the design and test of the body tube, the life of the body under the strongest load should be taken as the evaluation standard. The simulation results in this paper have certain guiding significance for further analysis of the problems such as swelling and swelling of the body.

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