Three-dimensional Simulation and Prediction of Solenoid Valve Failure Mechanism Based on Finite Element Model

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Abstract. The solenoid valve is a kind of basic automation component applied widely. It’s significant to analyze and predict its degradation failure mechanism to improve the reliability of solenoid valve and do research on prolonging life. In this paper, a three-dimensional finite element analysis model of solenoid valve is established based on ANSYS Workbench software. A sequential coupling method used to calculate temperature filed and mechanical stress field of solenoid valve is put forward. The simulation result shows the sequential coupling method can calculate and analyze temperature and stress distribution of solenoid valve accurately, which has been verified through the accelerated life test. Kalman filtering algorithm is introduced to the data processing, which can effectively reduce measuring deviation and restore more accurate data information. Based on different driving current, a kind of failure mechanism which can easily cause the degradation of coils is obtained and an optimization design scheme of electro-insulating rubbers is also proposed. The high temperature generated by driving current and the thermal stress resulting from thermal expansion can easily cause the degradation of coil wires, which will decline the electrical resistance of coils and result in the eventual failure of solenoid valve. The method of finite element analysis can be applied to fault diagnosis and prognostic of various solenoid valves and improve the reliability of solenoid valve’s health management.

1. Introduction

A solenoid valve (SV) is a basic automation component used in all works of life, which has many advantages such as small sizes, rapid transmission, various types, convenient for connection with computers [1]. At present, more research of solenoid valve in domestic and abroad are focused on work characteristics and structure design. Most of works lack specific quantitative analysis of key performance indicators to diagnose and predict the failure tendency of solenoid valve accurately, which increases the difficulty of prognostic and health management (PHM) for solenoid valves.

With the rapid development of computer technology and increasing perfection of finite element theory, finite element calculation has widely used in various research, especially in work characteristic simulation of solenoid valve. Some research use finite element software ANSYS to analyze saturation current of SV [2-5]. Some works calculate the relationship between coil numbers and electromagnetism by finite element software Multi-physics [6-8]. Some other papers present the
temperature calculation method of solenoid valve based on finite element model (FEM) [9, 10]. However, most previous research doesn’t consider using key performance indicators to monitor and predict working condition and remaining life of SV, which will easily cause the degradation failure of SV.

In this paper, take a direct acting solenoid valve as an example, a FEM is established by finite element software ANSYS Workbench to analyze the three-dimensional temperature and stress distribution of the SV. Some key performance indicators such as temperature, current, deformation are calculated. Based on the Workbench simulation, an accelerated life test of the SV is designed, and some key parameters are received, like electrical resistance and temperature. Kalman filtering algorithm is also introduced to the experimental data processing and then used to make comparison with simulation results. In this work, a prognostic method by monitoring electrical resistance of coils and temperature mutation is obtained and the optimization design of coils is put forward, which has significance for fault detection and diagnosis of SV, to some degree.

2. Numerical computation of finite element model

This paper takes the SLP, a kind of direct acting SV, as an example for modeling calculation and to solve the temperature field and stress field, and then to analyze parameters like temperature, stress, deformation, etc. The simplified geometry construction of this model machine and the cross-section in the accelerated life test is shown in Fig. 1

![Fig. 1 The geometric construction of the direct-action SV](image)

The direct acting SV is made up of coil, insulation, valve body, can, nut, spring, iron core, etc. For the convenience of model calculation, some assumptions are needed. The kind of thermal convection on the surface of the SV is natural thermal convection. The materials of different components in the SV are isotropic.

2.1. Mathematic model calculation of temperature field

The model takes the coil, iron core, insulation, can and some other main components as the study object. The SV geometry model in CAD is imported into the DesignModeler module in Workbench and then finite element mesh is generated by MESH module. The intelligent precision of mesh generation is 12 (Relevance=12). Considering the SV is axisymmetric, a quarter geometric model is selected to simulate and calculate the temperature field and stress field. Finite element mesh distribution of the SV is shown in Fig. 2
Joule heat generated in the SV can be transmitted by heat conduction, heat convection and heat radiation. The temperature rise of every component comes from the heat generation of coils by heat conduction, which can be calculated by the following equation: [11]

\[ Q' = \frac{Q}{V} = \frac{I^2 R}{V} = \frac{I^2 \rho L}{A^2 L} = \frac{I^2 \rho}{A^2} \]  

(1)

Where \( Q' \) is the volumetric heat generated, \( Q \) is the heat generated, \( I \) is the current, \( \rho \) is the electrical resistivity, \( V \) is the volume, \( L \) is the wire length, \( R \) is the electrical resistance of coils and \( A \) is the cross-sectional area. According to Fourier’s law, heat transfer rate between media can be expressed as [12]

\[ q_X = -kA \frac{\partial T}{\partial X} \]  

(2)

\[ q_Y = -kA \frac{\partial T}{\partial Y} \]  

(3)

\[ q_Z = -kA \frac{\partial T}{\partial Z} \]  

(4)

Where \( q_X, q_Y, q_Z \) are the heat transfer rates in the direction of X, Y and Z. \( k \) is the thermal conductivity of the media, \( A \) is the cross-sectional area of the media. External surfaces of SV contact with air directly and exchange heat by convection. To model the heat loss due to the convection from the surfaces of the SV, Newton’s cooling law (the following equation) is applied in the finite element model: [13]

\[ Q = hA(T_s - T_f) \]  

(5)

\[ h = \frac{k}{D} \left( 0.60 + \frac{0.387R_{\alpha}^{1/6}}{[1 + (0.559/R_{\alpha})^{9/15}]^{1/6}} \right)^2 \]  

(6)
Where $A$ is the surface area, $h$ is the heat convection coefficient, $T_s$ is the temperature of the SV external surfaces, $T_f$ is the temperature of air. Although the surface of the SV can receive heat from other components by heat conduction, the temperature difference between the surface of the SV and the ambient air will promote the heat exchange, making the steady-state thermal balance. Considering the order of magnitude of temperature rise in the SV is very small, the heat generated by radiation is pretty low. Thus, the heat radiation can be ignored. [14]

2.2. Mathematic model calculation of stress field

Due to the difference of material properties among components in the SV, stress will be generated with the temperature rise of every component which will cause the deformation in different directions. In the steady-state thermal stress analysis of ANSYS Workbench, the coupling relationship between temperature rise and stress change is built by three-dimensional Hooke’s law (the following equation). Due to the materials of the SV are isotropic, the relationship between strain $\varepsilon$ and stress $\sigma$ can be simplified as the following equation. For more convenient simulation in Workbench, constant $C$ will expressed by elastic modulus $E$, Poisson ratio $\mu$ and shear modulus $G$.

\[
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xy} \\
\sigma_{yz} \\
\sigma_{xz}
\end{bmatrix} + \partial \Delta T =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\
C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xy} \\
\varepsilon_{yz} \\
\varepsilon_{xz}
\end{bmatrix}
\]  

(7)

\[\Delta T = [\Delta T, \Delta T, \Delta T, 0, 0, 0]^T\]  

(8)

\[C_{11} = C_{22} = C_{33}\]  

(9)

\[C_{44} = C_{55} = C_{66}\]  

(10)

\[C_{12} = C_{23} = C_{31}\]  

(11)

\[C_{44} = C_{55} = C_{66} = 1/G\]  

(12)

\[G = \frac{1}{2(C_{11} - C_{12})} = \frac{E}{2(1 + \mu)}\]  

(13)

Where $E$ is the elastic modulus, $\mu$ is the Poisson ratio, $G$ is the shear modulus, $\partial$ is the thermal expansion coefficient, $\sigma_{xx}$, $\sigma_{yy}$, $\sigma_{zz}$ are the normal stress, $\sigma_{xy}$, $\sigma_{yz}$, $\sigma_{xz}$ are the shear strain, $\varepsilon_{xx}$, $\varepsilon_{yy}$, $\varepsilon_{zz}$ are the normal strain, $\varepsilon_{xy}$, $\varepsilon_{yz}$, $\varepsilon_{xz}$ are the shear stress. For isotropic materials, the relationship among temperature, stress and strain can be shown in the following equation:

\[\sigma_{xx} = \frac{1}{E} [\varepsilon_{xx} - \mu (\varepsilon_{xy} + \varepsilon_{xz}) + \partial \Delta T]\]  

(14)

\[\sigma_{yy} = \frac{1}{E} [\varepsilon_{yy} - \mu (\varepsilon_{xy} + \varepsilon_{xz}) + \partial \Delta T]\]  

(15)
Considering the coupling effect of temperature and stress, a sequential coupling method is applied in the model. After the temperature field is built, the temperature of every component will be regarded as the new load to build the stress field. The steps of building the finite element model is shown in the Fig. 3

\[
\sigma_{zz} = \frac{1}{E} \left[ \varepsilon_{zz} - \mu (\varepsilon_X + \varepsilon_Y) + \partial \Delta T \right] \\
\sigma_{xy} = 1/G \varepsilon_{xy} \\
\sigma_{yz} = 1/G \varepsilon_{yz} \\
\sigma_{zx} = 1/G \varepsilon_{zx}
\]

Choose the module type in Toolboxes, import the geometry model of the SV to Workbench, define materials. Mesh distribution Relevance=12, Element size=2mm, Behavior=soft. Success of mesh distribution? Apply loads, solve temperature field

Add the temperature as new load to solve stress field

Use the postprocessor to display the temperature field and the stress field color contour image and data

End the calculation

**Fig. 3** Steps of building the finite element model

Firstly, Choosing Steady-State Thermal module and Static Structural module as the analysis types in Workbench Toolboxes and importing the geometry model of the SV from CAD to Workbench, then materials need to be defined. Secondly, dividing the mesh. If mesh distribution succeeds, applying loads (electrical resistivity, electrical resistance of coils, thermal conductivity, etc) to the SV and then solving the temperature field. If mesh distribution fails, restarting the mesh distribution is needed. Thirdly, applying stress loads (E, μ, etc) and the average temperature rise of every component as the new load to the SV. Then the stress field needs to be solved. Fourth, using the postprocessor to display the color contour image and data of the temperature field and the stress field. Finally, end the model calculation.

2.3. *Kalman filtering algorithm*

During the finite element simulation and the accelerated life test, although the relative parameters (temperature, electrical resistance, current, etc) of the SV are monitored, the process noise and the deviation of data tested by sensors can’t be avoided. Thus, data processing will be essential to eliminate noise and restore real signals. Take the parameter of electrical resistance as an example, the state equation and observation equation (the following equation) is built.

\[
X(k) = AX(k - 1) + BW(k - 1)
\]
\[ Z(k) = HX(k) + V(k) \]  \hspace{1cm} (21)

Where \( X(k) \) is the variable of electrical resistance, \( A = H = B = 1 \). \( W(k) \) is the process noise, \( V(k) \) is the test noise. Kalman filtering is used to predict the time of \( k \) according to the time of \( (k - 1) \). The electrical resistance changes before and after Kalman filtering is shown in Fig.4. According to the theoretic calculation, the resistance of coils should be 38Ω. However, the true value will be changed with the variation of environment. The noise and random error also make the value changed continuously, which will provide an observed value. After using Kalman filtering in the data process, the value of electrical resistance (Kalman filtering value) will be closer to the true value. The Fig.5 shows Kalman filtering deviation is lower than measuring deviation obviously, which can restore data information accurately and will be used in the following data processing of the accelerated life test.

![Fig. 4 Resistance value before and after Kalman filtering](image1)

![Fig. 5 Resistance deviation before and after Kalman filtering](image2)

3. **Results of numerical simulation and the accelerated life test**

According to the FEM, the finite element software Workbench is used to calculate the temperature and stress field. The three-dimensional temperature field of the SV is shown in the Fig.6 when 0.25A of current is provided. The highest temperature rise is in the coil, which is 110.4 ℃. The lowest temperature rise is on the surface of the SV, which is 88.009 ℃. The temperature decreases progressively from internal coils to external can. Temperature rise of every component comes from
heat generation of coils, which makes the temperature rise of coils is the highest. The surface of the SV contacts with ambient air directly that will generate the natural thermal convection and cause heat loss on the surface.

Fig. 6 Three-dimensional temperature distribution (0.25A)

Fig.6 has revealed that the coil of the SV can generate high temperature. Changing the driving current, the temperature distribution of the coil is shown in the Fig.8. Although the material in the coil is the same, there is still temperature difference between coil wires. The uneven heat distribution and temperature difference can easily cause degradation even failure of coils with the continuous work of the SV. As the driving current goes up from 0.25A of current to 1A of current, the temperature of coils rises correspondingly, as the Fig.7 shows. The electro-insulating rubbers, covering the surface of the coil, is used to protect coils from short-circuit in the SV. If the high temperature of coils exceeds the threshold of electro-insulating rubbers, the electro-insulating rubbers will melt. Thus, selecting proper materials of the coil and the electro-insulating rubbers has much significance for prolonging life of the SV.
Applying relative stress loads and the average temperature of every component as new loads to the SV and solving the stress field. Fig.8 shows the three-dimensional stress distribution of the SV when 0.25A of current is provided. The highest stress is in the junction between the can and the insulation, which is 0.37557MPa. Due to the different material properties among components, like elastic modulus $E$ and Poisson ratio $\mu$, the stress caused by thermal expansion will also be different. Especially, the big stress difference between coil wires will cause the coil squeezing against each other and make the electro-insulating rubbers generate high force loads, easily resulting in the deformation in different directions, as the Fig.9 shows.

Fig. 7 Temperature distribution of the coil

Fig. 8 Three-dimensional stress distribution (0.25A)

Fig. 9 Three-dimensional stress deformation (0.25A)
The simulation results suggest a kind of degradation mechanism of the SV. On the one hand, the coil can generate the high temperature and easily exceed the thermal limit of electro-insulating rubbers with the continuous work of the SV, finally fail the insulation. On the other hand, the uneven distribution of thermal stress in coils will make coil wires squeeze against each other. When the electro-insulating rubbers, which have already damaged by thermal stress, squeeze against each other, the short circuit of the coil will happen and gradually the electrical resistance will be declined, finally causing eventual degradation failure of the SV.

The useful life of the coil is 4~10a when the SV works continuously in the normal temperature.\textsuperscript{[15]} The remaining life will be reduced remarkably while the temperature rises 8~10°C. Based on the results of the finite element simulation, this paper designs the accelerated life test of the SV to prove the validity of the prediction.

When the SV works normally, the data comparison of average temperature rise between the finite element simulation and the accelerated life test is shown in Table 1. $I_i$ is the driving current, $T_s$ is the temperature of finite element simulation, $T_e$ is the temperature measured from the experiment, which has been processed by Kalman filtering. $T_e'$ is the temperature data from the experiment without being processed. If Kalman filtering is introduced, the maximum of relative error is 1.91% while the maximum of relative error without data processing is 8.27%. The Table 1 suggests that Kalman filtering is needed in data processing to receive more accurate data for further analysis. Meanwhile, the data from finite element simulation and the accelerated life test are almost consistent, which proves the simulation result can be verified through the experiment.

| $I_i$/A | $T_s$/°C | $T_e}$/°C | $T_e'$/°C | Relative error $|T_s - T_e|/T_s$ | Relative error $|T_s - T_e'|/T_s$ |
|--------|----------|----------|----------|-----------------|-----------------|
| 0.25   | 110.40   | 112.56   | 119.26   | 1.91%           | 8.27%           |
| 0.5    | 218.81   | 216.56   | 209.37   | 1.04%           | 4.50%           |
| 0.75   | 327.21   | 325.26   | 311.14   | 0.60%           | 5.16%           |
| 1.0    | 435.61   | 438.01   | 452.81   | 0.54%           | 3.80%           |

Take the 0.25A of driving current as an example to predict a kind of degradation mechanism of the SV. The change of electrical resistance when the SV is failing is shown in the Fig. 10.

![Fig. 10](image_url)

**Fig. 10** The failure variation of coil resistance (0.25A)

The figure shows there are several mutations of coil resistance and has a tendency of constant decline. With the open and close of the valve continuously, the electro-insulating rubbers covering on
the surface of coils will appear the degradation. The thermal stress generated by thermal expansion will also cause the deformation of the coil making the coil squeeze against each other. When the coils, whose electro-insulating rubbers have already damaged by thermal stress, squeeze against each other, the short-circuit of the coil will happen due to the lack of protection of electro-insulating rubbers and the electrical resistance of coils will be declined gradually along with several mutations.

Once the coil resistance declines, the driving current will rise because of the constancy of driving voltage, which will make the coils generate more heat and new temperature rise. The failure variation of coil temperature is shown in Fig. 11. With the rise of coil temperature, the electro-insulating rubbers will be further damaged. Coupling with the thermal stress, the coils whose electro-insulating rubbers have already damaged by thermal stress will squeeze against each other, causing short-circuit of more coils and the coil resistance will decline once again. When the new temperature of coils exceeds the threshold of electro-insulating rubbers with the continuous rise of temperature after several thermal cycles, a mass of electro-insulating rubbers will be damaged, causing the decline of coil resistance sharply. When the electromagnetic force of iron core is lower than its threshold, the iron core will not overcome the elasticity to move up and down and finally the failure of the SV will happen.

According to the material properties provided by manufacturers, the minimum of temperature to fail the coil wires exceeds 350°C while the temperature rise of coils is under 300°C in the normal driving current. Thus, the failure of the coil material is not the root cause. By comparing and analyzing the results of the simulation and the accelerated life test, a kind of degradation mechanism of the SV can be proposed. When the coil comes to fail, the electrical resistance of coils will have the tendency of decline and the average temperature of coils will have several rise of mutation. In the life-circle of the SV, monitoring the electrical resistance and the temperature change are effective methods to predict faults and prolong life. Meanwhile, selecting proper materials of electro-insulating rubbers can also improve reliability of the SV.

![Fig. 11 The failure variation of coil temperature (0.25A)](image)

\section{4. Conclusion}

A three-dimensional finite element model of thermo-structure coupling is built based on ANSYS Workbench that is able to predict the temperature, stress, deformation, etc. Kalman filtering algorithm is introduced to the data processing and the result shows this algorithm can effectively reduce measuring deviation and restore more accurate data information. By comparing and analysing the results of the simulation and the accelerated life test, a kind of failure mechanism of the SV is put forward and the optimization design of electro-insulating rubbers is also proposed. The high temperature generated by continuous driving current and the thermal stress caused by thermal
expansion can easily result in the degradation of coil wires, which will decline the electrical resistance sharply and rise the temperature of coils rapidly along with several mutations. Thus, monitoring the parameters like temperature and electrical resistance has significance to improve reliability of the SV and do research on prolonging life.

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