

The Simulation Analysis of Thermo-Mechanical Coupled Stress for Wet Clutch Friction Plate Based on ABAQUS

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Abstract: In this paper, we firstly provide a brief introduction on the research status and progress of the thermo-mechanical coupled properties and the actual work process of a wet clutch; we adopt specific research methods to analyze the friction structure and material properties, moreover, appropriate analysis will be made for the working condition analysis, stress features, the causes and factors of thermo-mechanical coupled, and constructing dynamics model under transient conditions. We also research the principles and processes for solving coupled stress, which enable us to obtain the simulation analysis model (Analysis steps, Boundary conditions, Contact algorithm, load, Mesh, Quality scaling factor) based on ABAQUS software. We also further analyze the thermo-mechanical coupled stress and get results from the temperature field, stress field, integrated displacement, axial stress distribution of the dual steel plate and friction plate. At last, we use the results to compare and validate the results of indirect method (ANSYS method), which provides the necessary theoretical basis and guidance for subsequent simulation. *Copyright © 2013 IFSA.*

Keywords: Thermo-mechanical coupled, Wet clutch friction plate, ABAQUS, Stress simulation analysis.

1. Introduction

In recent years, many researches have been done on the problem of wet clutch thermo-mechanical, which mainly includes theoretical study and experimental research [5]. Theoretical study is divided into two categories: analytical method and finite element method. In this study, the analytical method will be used initially to make a thermo-mechanical analysis for the thermal coupling phenomena, and thermo-elastic will be used to establish temperature field theory equations of heat and thermal stress equations and solve them [7]. With the continuous development of finite element techniques, computer is wildly used for studying wet friction clutch shift numerical simulation, which is

considered as the primary means of friction coupled thermal characteristics of the present study [13]. Since the actual operation of the wet clutch, the thermal deformation of the friction surface has made contact pressure changing of the contact surfaces [8]. The contact pressure is uneven, which in turn affects the distribution of temperature fields. It is a typical problem of thermo-mechanical coupling multi-physics fields. Therefore, we need to understand the structural characteristics of friction pair and the force characteristics of various conditions by using direct thermal coupling method to analyze coupling characteristics during sliding friction.

In the actual working process of a wet clutch, the sliding friction velocity is different at all stages of its operation [10]. Therefore, the numerical analysis

method from finite element theory will be gradually applied to wet friction clutch in thermal coupling characteristics. In domestic, an unsteady temperature field calculation physical and mathematical models of dual wet clutch shift steel will be established, which provides the necessary precondition for the further calculate the stress field and thermal deformation [9]. The process of wet friction clutch slip friction is analyzed, while the friction surface temperature rises, and thermal failure may cause problems for the process of sliding friction heat load characteristics [6], however, this method will not be considered to change the friction coefficient of sliding friction during the movement.

In this paper, on the basis of the above work, it needs to establish ABAQUS finite element model by the wet clutch pair, using direct coupling method to study in-depth thermal coupling characteristics during slipping [4]. We can obtain the deformation of the friction pair, the distribution of stress field and temperature field. This paper will compare and validate the calculation results of indirect method. Specific research methods are as follows [2]:

1) In-depth study the structural characteristics and working conditions of the wet clutch, construct the dynamic model of a wet clutch shifting process. Analyze the reasons for the process of the sliding friction heat generated by the coupling phenomenon. Determine the impact factors of coupled stress field and provide the necessary theoretical basis and guidance for subsequent simulation.

2) Use ABAQUS software to build a wet clutch pair three-dimensional finite element model. Determine the appropriate mass scaling factor in the analysis step. Apply contact properties, boundary conditions, loads and its interaction conditions and mesh. Finally, we use the direct coupling method to complete the simulation process of sliding friction.

3) By calculating, we obtain the distribution characteristics of the friction plate and dual steel contact surface temperature field, stress field and the deformation rule of friction coupled. We compare and validate the calculating results of indirect method, identify and analyze the reasons for the errors.

2. The Thermo-mechanical Coupled Mechanism of Wet Clutch

2.1. Friction Structure and Material Properties, Working Conditions Analysis and Stress Features

2.1.1. Friction Structure and Material Properties

Wet clutch friction is composed of friction plate and dual steel plate, which are shown in Fig. 1. Friction structural parameters are listed in Table 1. Material properties are listed in Table 2.

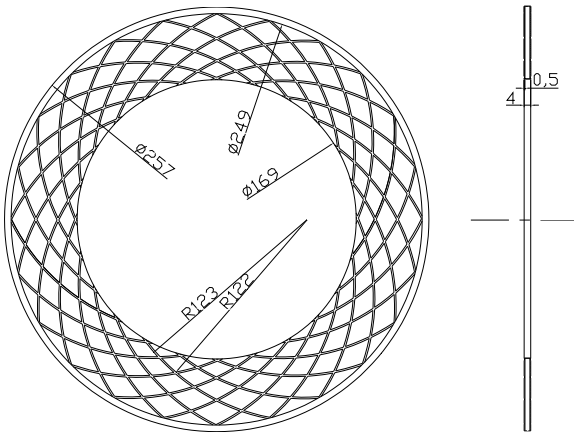


Fig. 1. Structure Diagram of the Friction Plate.

Table 1. Friction Structural Parameters.

	Outer radius (mm)	Inner radius (mm)	Thickness (mm)
Dual steel plate	0.1245	0.0845	0.004
Friction plate	0.1245	0.0845	0.004

Table 2. Material properties.

	Dual steel plate	Friction plate
Density $\rho / kg \cdot m^{-3}$	7800	5600
Specific heat capacity $c / J(kg \cdot ^\circ C)^{-1}$	487	536
Heat conductivity coefficient $\lambda / W(m^\circ C)^{-1}$	-	30
Coefficient of thermal expansion $/ 10^{-5}$	1.27	1.30
Elasticity modulus $E / 10^{11} Pa$	1.6	1.1
Poisson's ratio μ	0.29	0.30

2.1.2. Working Condition Analysis and Stress Features

According to the oil film thickness variation of the friction process of friction sliding, transient condition can be roughly divided into three phases: liquid friction stage, mixed friction stage and boundary friction stage. The friction characteristics of the three different stages and the dual steel plate and friction plate force situation are somewhat different, as shown in Fig. 2.

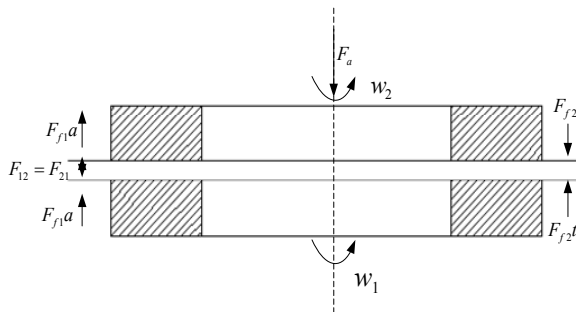


Fig. 2. Force Diagram of the Friction.

2.2. Dynamics Model Under Transient Conditions

According to the working conditions and force status of friction sliding process under transient conditions transition, we can build the following equations [3]:

$$\left(m_c + z \sum_{i=1}^z (m_1 + m_2) \right) \ddot{x} = F_c + F_w - F_{spring} - (F_{f1} + F_{f2}) \operatorname{sgn} \dot{x} - F_{seal} \operatorname{sgn} \dot{x}; 0 \leq x \leq z\delta_0 \quad (1)$$

In equation (1), m_c is the piston weight, kg; m_1 is the dual steel plate weight, kg; m_2 is the friction plate, kg; z is the practical work of friction pair; $\ddot{x}$ is the acceleration, m/s^2 ; F_c is the piston hydraulic, kg; F_w is the oil centrifugal force; F_{spring} is the return spring resistance; F_{seal} is the friction between the piston and seal; F_{f1} , F_{f2} Friction force of driving gear and driven gear between friction plate and dual steel plate, as shown in Fig. 3. We can also obtain the simplified torsion dynamics model after simplifying as shown in Fig. 4.

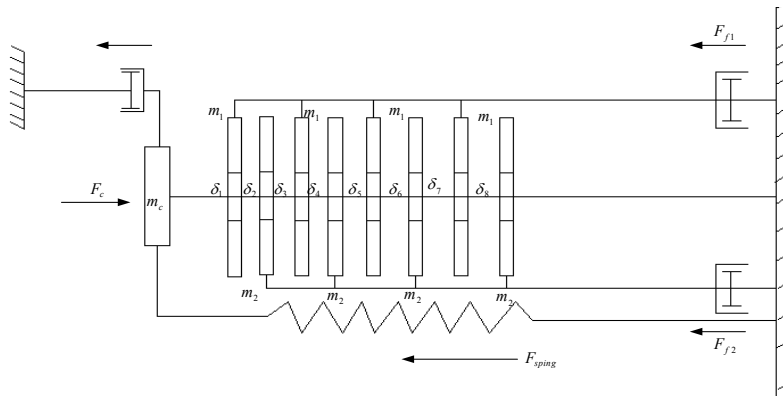


Fig. 3. Dynamics model under transient conditions.

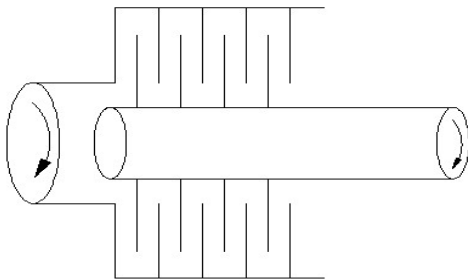


Fig. 4. Simplify torsion dynamics model.

2.3. The Causes and Factors of Thermo-Mechanical Coupled

2.3.1. The Causes of Thermo-mechanical Coupled

With the relative rotational speed changing between dual steel friction plate and friction plate, friction contact surfaces are subjected to an axial pressure and generate a large amount of frictional heat and the temperature of the friction plate rises

rapidly. Temperature will cause thermal stress and deformation. Heat generated by friction depends on the size of the contact pressure; there is a strong coupling relationship between temperature and stress fields, and the two inter-conditionals are mutually influenced.

2.3.2. The Factors of Thermo-mechanical Coupled

Analyzing the coupling between temperature and stress fields often needs to consider the heat conduction equations and dynamic equations of balance. In the process of friction pair sliding friction, the contact surface temperature difference ΔT will cause a thermal expansion ε_0 , $\varepsilon_0 = \alpha \Delta T$, of which, α is the coefficient of thermal expansion. Friction heat is closely related to the friction coefficient, the speed difference, the contact surface pressure and other factors. In summary, this is a very complex coupling process problem, as shown in Fig. 5.

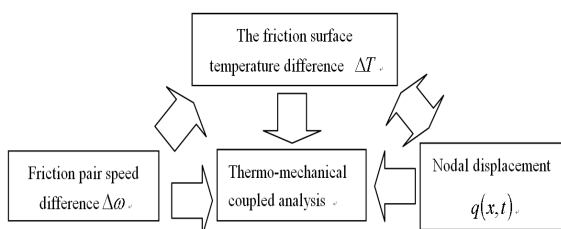


Fig. 5. The factors of coupled fields.

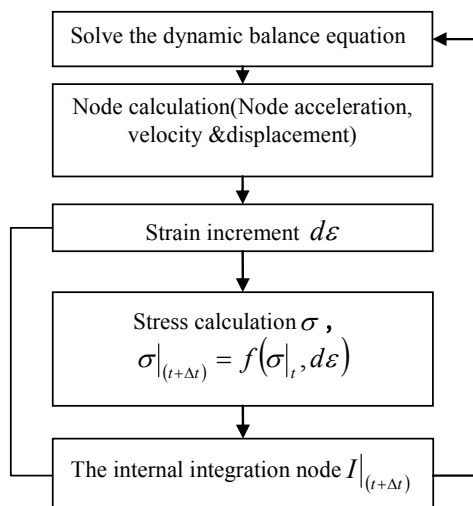


Fig. 6. Explicit dynamics calculation process.

3. The Simulation Analysis Thermo-mechanical Coupled Stressed for Wet Clutch Friction Plate

3.1. Principles and Processes for Solving Coupled Stress

Explicit dynamics is applied to solve high-speed dynamics, complex contact problems and highly nonlinear quasi-static problems. Explicit dynamics uses central different equations of motion explicit time integration and above-mentioned incremental step kinetic conditions as basis to calculate next incremental step dynamic conditions and dynamic equilibrium equation [11]:

$$M \ddot{u} = P - I \quad (2)$$

The node acceleration of t time:

$$\ddot{u}|_{(t)} = (M)^{-1} (P - I)|_{(t)} \quad (3)$$

Incremental step midpoint rate:

$$\dot{u}|_{\left(t+\frac{\Delta t}{2}\right)} = \dot{u}|_{\left(t-\frac{\Delta t}{2}\right)} + \frac{(\Delta t|_{t+\Delta t} + \Delta t|_{(t)})}{2} \ddot{u}|_{(t)} \quad (4)$$

The nodal displacements of incremental step end:

$$u|_{(t+\Delta t)} = u|_{(t)} + \Delta t|_{(t+\Delta t)} \dot{u}|_{\left(t+\frac{\Delta t}{2}\right)} \quad (5)$$

The main calculation process shown in Fig. 6.

3.2. The Simulation Analysis Model

1) Set analysis steps.

Use ABAQUS software to establish dual steel friction plate and friction plate, which is three-dimensional model of the elastic deformation body, as shown in Fig. 7. According to the three friction phase of transition conditions, we set four analysis steps: Step 1 (0.001 s), Step 2 (0.0226 s), Step 3 (0.1 s), Step 4 (0.4728 s).

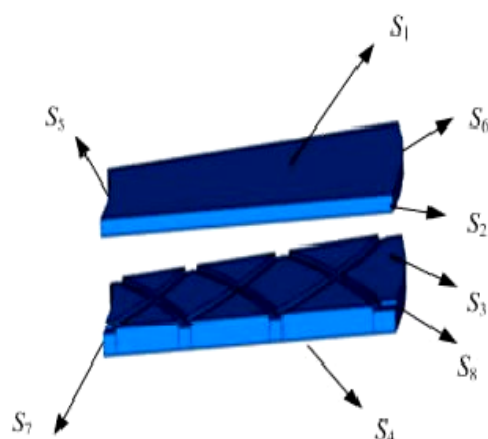


Fig. 7. Three-dimensional geometric model of friction.

2) Define boundary conditions.

As shown in Fig. 7, the heat exchanges S_7, S_8 with the external environment of friction plate inner but the outer will not be considered. According to the actual working situation, set an initial temperature of 70 °C for friction conditions.

3) The contact and algorithm.

Common contact method and main surface contact method can be used for creating contact pairs in the interaction module. In this paper, a common contact method will be adopted. The role of oil, in a large part, with ever-changing state of contact, directly affects the contact area. The following displacement and stress constraints will be imposed on the contact surface of each pair of nodes [1]:

$$\begin{cases} w_i = w_j, P > 0 \\ w_i \neq w_j, P = 0 \end{cases} \quad (6)$$

In the same way, each node on the contact surface is also vice-imposed the following temperature and heat flow constraints:

$$\begin{cases} T_i = T_j, P > 0 \\ T_i \neq T_j, P = 0 \\ q = \mu \omega r P = -(q_{ni} + q_{nj}), P > 0 \\ q = 0 = q_{ni} = q_{nj}, P = 0 \end{cases} \quad (7)$$

4) Apply load.

In order to achieve the dual steel rotating, a reference point RP in the center of the torus friction contact surface will be created to establish rigid constraints between the dual steel and RP so as to obtain rigid body displacement. Oil pressure is applied as shown in Fig. 8 in friction plate structure symmetry plane.

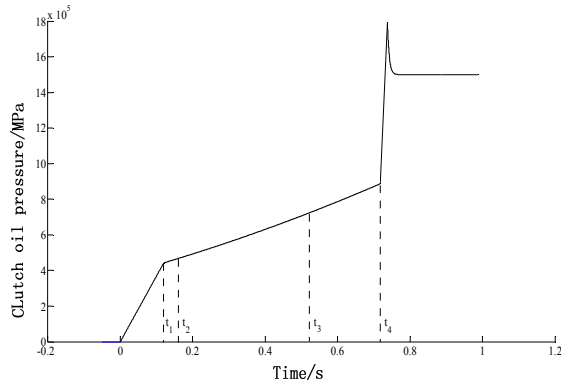


Fig. 8. Oil pressure load.

5) Meshing.

In this simulation model, the partition function will contribute to divide the friction plate and set the global seed. Use advanced algorithms for friction slices swept meshing and use the wedge unit in the transition area division, as shown in Fig. 9.

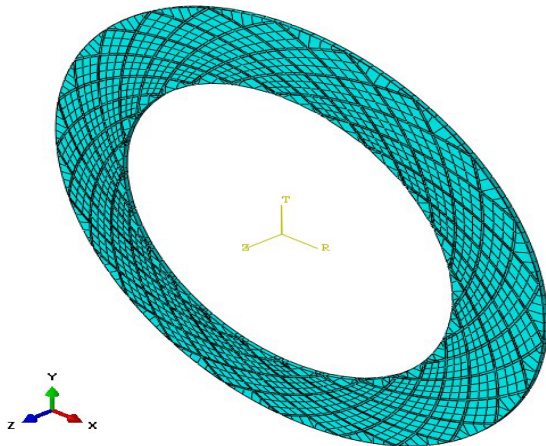


Fig. 9. Friction plate meshing.

6) Quality scaling technology.

The key of quality scaling technology lies in scaling factor. A scaling factor with too small mass

cannot effectively shorten the calculation time, while a scaling factor too large mass will lead to a sharp increase in structural inertia loads; even in the calculation process it cannot converge. When the simulation is calculated using the central difference method, the convergence must meet certain conditions [12]:

$$\Delta t \leq \Delta t_{cr} \leq \frac{T_n}{\pi} \quad (8)$$

Since the grid cell differs in sizes, the calculation time is different, and the shortest time is the critical time step increment Δt_{cr} . According to the

$$\Delta t = \frac{L_{min}}{C_d}, \quad C_d = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \quad \lambda = \frac{Ev}{(1+\nu)(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)}.$$

So we can get:

$$\Delta t_{cr} = \frac{L_{min}}{\sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}} \quad (9)$$

At last, the length calculating time t is determined by the number of time increments step n , it is

$$n = \frac{T}{\Delta t_{cr}} \quad (10)$$

This quality scaling technology is used to ensure the stability and accuracy of the entire calculation results of the analysis process, which greatly improves the computational efficiency and shortens the calculation time. Mass scaling factor is a , while the quality is a magnification in the calculation process. The step will increase the time increment by $\sqrt{a}$ times. Mass scaling of the simulation each step is shown in Table 3:

3.3. The Stress Analysis of Thermo-Mechanical Coupled

Energy conservation equations of continuum:

$$\int_V \rho v_i \frac{\partial v_i}{\partial t} dV + \int_V \frac{\partial \rho}{\partial t} U dV = \int_V \rho (\bar{Q} + b_i v_i) dV + \int_S (P_i V_i - H) dS \quad (11)$$

We also obtain the energy conservation equations of thermo-mechanical coupled analysis:

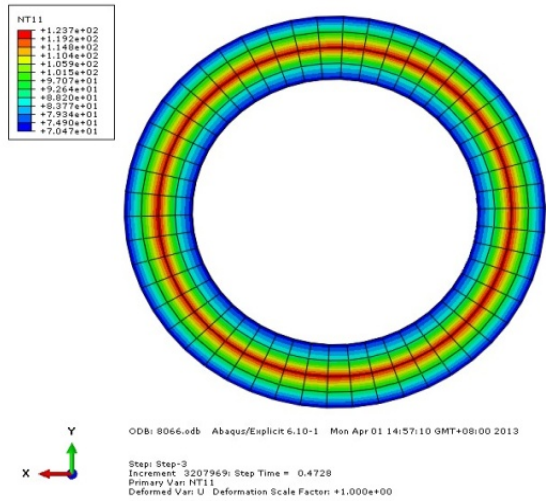
$$\begin{aligned} \int_V \left\{ \rho \left(\bar{Q} - \frac{\partial U}{\partial t} \right) + \sigma_{ij} \frac{\partial v_i}{\partial x_j} \right\} dV &= \int_S H dS \\ \Rightarrow \int_V \rho_{ij} \frac{\partial \delta u_i}{\partial x_j} dV &= \int_V \rho b_i \delta u_i dV + \int_V \rho \frac{\partial v_i}{\partial t} \delta u_i dV \end{aligned} \quad (12)$$

Table 3. Mass scaling factor.

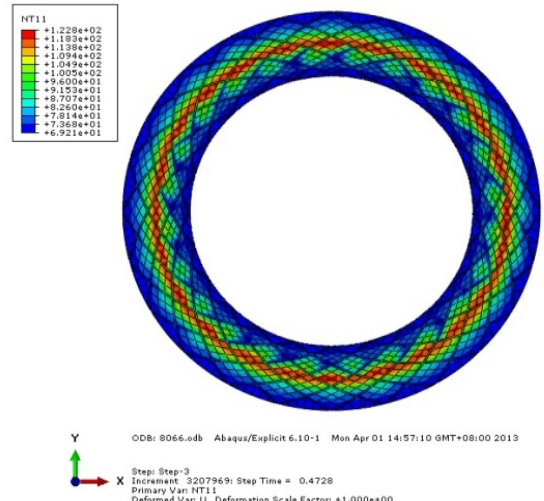
	Region	Type	Frequency/Interval	Factor	Increment
Step 1	Poor F	Target time	Beginning of Step	16	
	Poor C	Target time	Beginning of Step	8	None
Step 2	Poor F	Target time	2500 intervals	None	1e-7
Step 3	Poor F	Target time	2500 intervals	None	1e-7
Step 4	Poor F	Target time	2500 intervals	None	1e-7

Calculated by solving the iterative loop, we can get the temperature field distribution of friction plate and dual plate steel contact surface at the end of friction as shown in Fig. 10 (a), Fig. 10 (b). Lowering the temperature on both sides, there is a large contact surface temperature gradient. We can also get the stress field distribution of friction plate and dual plate steel

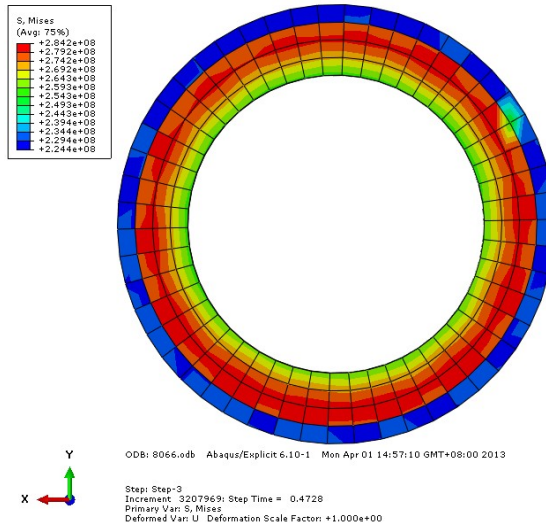
contact surface at the end of friction as shown in Fig. 10 (c), Fig. 10 (d). We can acquire the integrated displacement distribution of friction plate and dual plate steel contact surface at the end of friction as shown in Fig. 10 (e). We can obtain the axial stress distribution of friction plate and dual plate steel contact surface at the end of friction as shown in Fig. 10 (f).



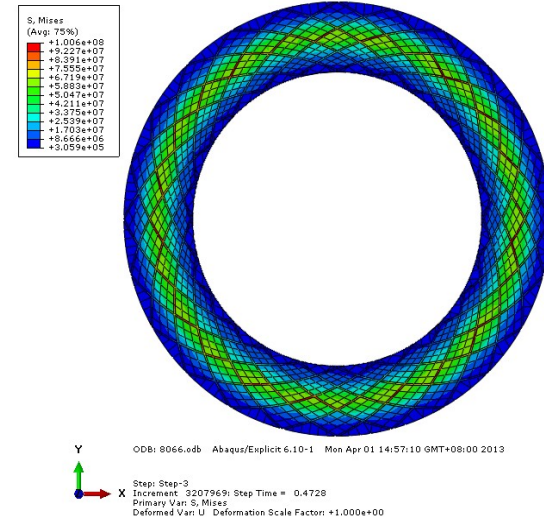
(a) Dual steel plate temperature field distribution.



(b) Friction plate temperature field distribution.

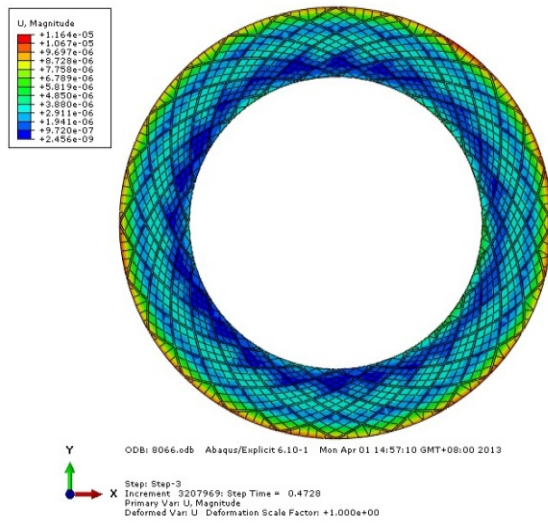


(c) Dual steel plate stress field distribution.

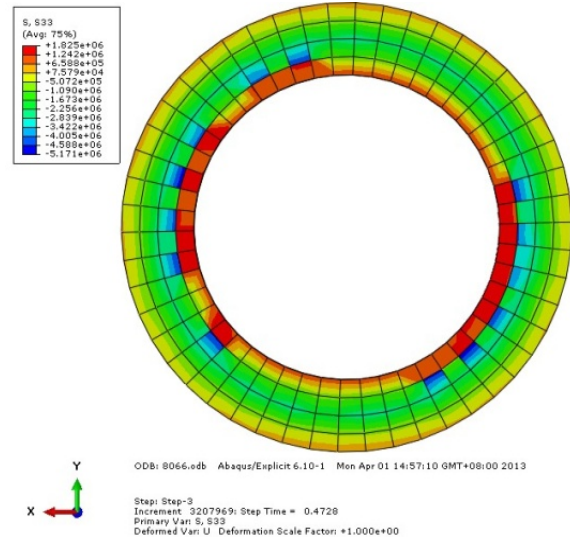


(d) Friction plate stress field distribution.

Fig. 10 (a-d). Thermo-mechanical coupled field distribution.



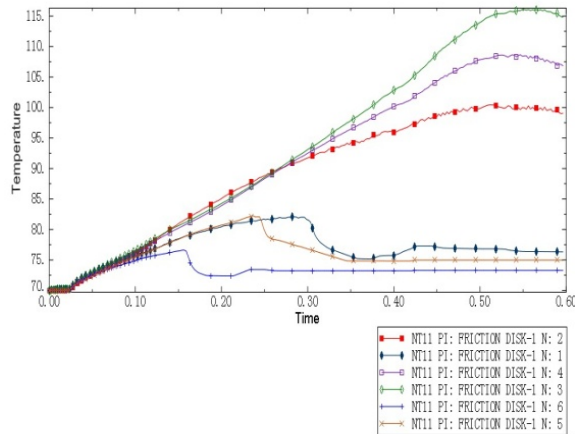
(e) Dual steel plate integrated displacement distribution.



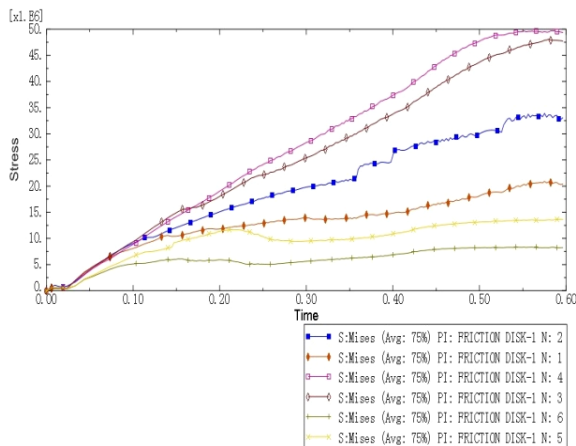
(f) Friction plate axial stress distribution.

Fig. 10 (e-f). Thermo-mechanical coupled field distribution.

Selecting 6 radial node of friction plate, we acquire the temperature and overall stress curve with time as shown in Fig. 11.



(a) Friction plate node temperature change curve.



(b) Friction plate node stress change curve.

Fig. 11. Thermo-mechanical coupled node curve.

4. The Comparative Research of Simulation Results

ANSYS finite element analysis is used to conduct indirectly software analysis. We get temperature field, stress field, the integrated displacement distribution of liquid friction stage, mixed friction stage and boundary friction stage under transient condition. In order to compare the results for ABAQUS direct analysis and calculation, we identify and analyze the error reasons. In the same way, we select 6 radial node of friction plate.

4.1. The Comparative Analysis of Temperature Field Simulation Results

We can get the friction plate curve of temperature field each node in the radial, as shown in Fig. 12.

4.2. The Comparative Analysis of Stress Field Simulation Results

We can get the friction plate curve of stress field each node in the radial, as shown in Fig. 13.

4.3. The Comparative Analysis of Integrated Displacement Simulation Results

We can get the friction plate curve of integrated displacement each node in the radial, as shown in Fig. 14.

With the direct method of contacting with friction plate surface temperature, the stress field distribution is very uneven, and regions between temperature and stress gradient are greater.

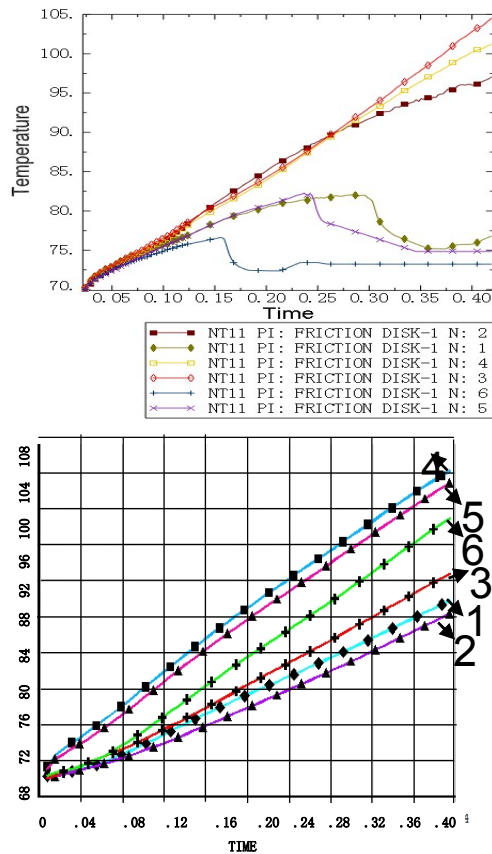


Fig. 12. The comparative analysis of temperature field simulation results.

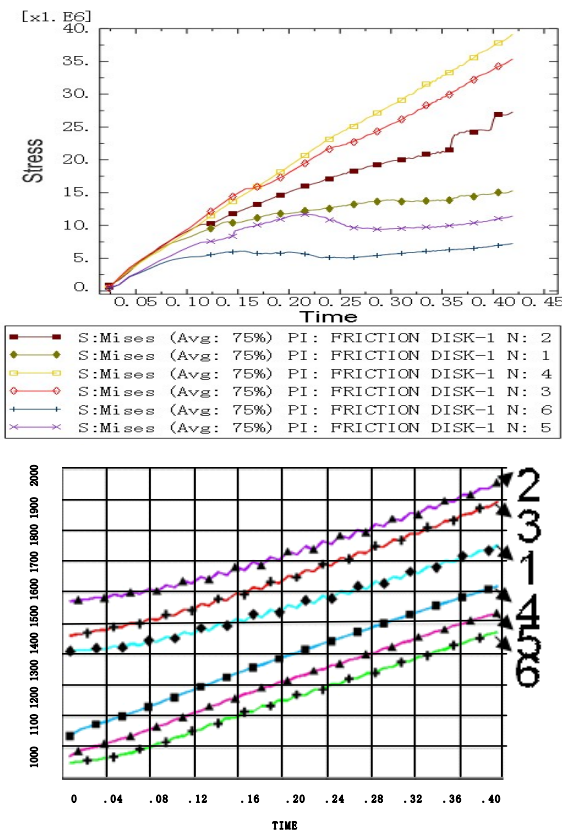


Fig. 13. The comparative analysis of stress field simulation results.

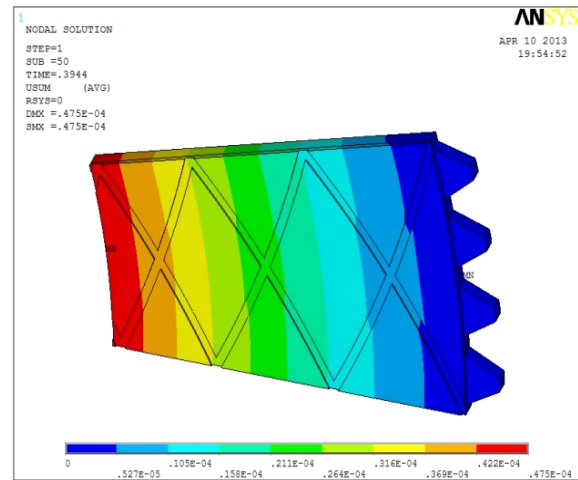


Fig. 14. The comparative analysis of integrated displacement simulation results.

The results of the direct method better reflect the impact of sliding friction process of thermo-mechanical coupled. Friction plate has a certain degree of warpage, because of the role of external constraints with the effect of inertia loads, under the indirect method integrated displacement larger inner lining.

5. Conclusions

This paper briefly introduces the research status and progress of the thermo-mechanical coupled properties. The dynamic model is established in accordance with the structural characteristics and stress characteristics of the wet clutch friction of various conditions. The principles and methods involved in the process are used to analyze thermo-mechanical coupled characteristics. ABAQUS software is adopted to establish friction-dimensional finite element model. Direct coupling method is used to obtain deformation rule of friction fair, the distribution principle of stress field and the temperature field. This paper compares and validates the results of indirect method, points out the distinction between direct and indirect methods and further analyzes the reasons. Meanwhile, the cited quality scaling technology is used to improve the efficiency of the entire simulation calculations. This paper provides the necessary theoretical basis and guidance for subsequent simulation.

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