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One-way Thermal-Fluid-Solid Coupling Analysis of Helicopter Tail Reducer with Spiral Bevel Gear

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ABSTRACT

This research focuses on investigating the thermal-fluid-solid coupling behavior within spiral bevel gears to enhance the bearing capacity and extend the operational service life of the gear reducer located in the helicopter tail gearbox. The study commences by constructing detailed, parametrically defined three-dimensional digital models. These models accurately represent the critical components: the spiral bevel gear itself, the surrounding gearbox housing, and the supporting gear shaft, based directly on the specifications of an actual helicopter tail reducer assembly. Subsequently, the analysis proceeds with a one-way, steady-state thermal-solid coupling simulation performed on the established model assembly. This critical simulation phase aims to realistically replicate the thermal energy transfer process, explicitly treating the lubricating oil circulating within the system as the primary heat generation source. Simultaneously, it evaluates the consequent structural response and mechanical deformation of the gear reducer components under the influence of this sustained thermal loading. Crucially, during this computational analysis phase, the material properties and parameters specific to the gear alloy are meticulously incorporated. This inclusion is vital for achieving more precise and reliable predictions concerning the resultant thermal stress fields and deformation distributions throughout the gear structure. The investigation successfully elucidates the significant impact of heat flux magnitude and distribution on the overall structural stability and integrity of the gearing system. These findings furnish a robust theoretical foundation essential for optimizing future gear design parameters and enhancing performance reliability under demanding real-world operational conditions encountered in helicopter applications.

Keywords: *Helicopter tail reducer, spiral bevel gear, thermal-fluid-solid coupling, FEA*

I. Introduction

With the continuous development of helicopter technology and the increasing performance requirements, it is particularly important to optimize the performance and reliability research of the tail gearbox, which is a key component of helicopters. As a power transmission device connecting the rotor and tail rotor, the tail gearbox has internal spiral bevel gears. These gears work under high - speed rotation and large loads, and endure extremely severe mechanical and thermal stress tests. The failure of these gears has a significant impact on helicopter performance in terms of both flight safety and maintenance costs. Therefore, in - depth research on the thermal - fluid - structure coupling behavior of spiral bevel gears in helicopter tail gearboxes has great theoretical and practical significance for improving the bearing capacity and service life of gears and enhancing the overall performance of the helicopter.

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Initial computational investigations into transient lubricant behavior within gear systems were first recorded in 2007 using numerical modeling techniques [1]. Later studies utilized fluid dynamics simulations to analyze aerodynamic power dissipation in spur gears operating within gaseous media [2]. Researchers subsequently created a three-dimensional multiphase flow model for gearbox fluids employing ICEM CFD meshing, integrating turbulence modeling via CFD to quantify spur gear aerodynamic losses [3]. Improved grid generation methods were then implemented to enhance simulation accuracy for meshing gear systems, facilitating comparisons between computed thermal distributions and long-duration experimental temperature measurements [4]. Additional research explored oil-immersion operating conditions, leveraging open-source computational tools to assess parameter influences on energy dissipation during gear churning [5]. Sophisticated modeling approaches arose through finite-volume CFD simulations of lubricant distribution in FZG-test single-stage gearboxes, integrating biphasic flow dynamics and validating outcomes against both power loss data and high-speed imagery [6]. Coupled thermoelastic finite-element models enabled thermal-stress interaction analysis for spiral bevel gears, incorporating frictional heating to forecast transient temperature patterns during tooth engagement [7]. Dynamic meshing techniques in Fluent CFD software were employed to study transient flow in locomotive transmissions, simulating oil-bath lubrication dynamics [8]. Non-Newtonian lubrication principles were later combined with numerical validation to evaluate crowned herringbone gear performance under diverse operating and geometric parameters [9]. Recent progress features multiphase flow simulations for high-speed train gearboxes using VOF modeling with RNG k-ε turbulence and deformable meshing, enabling pressure variation analysis during gear meshing [10]. Detailed finite-volume models of planetary gear systems were developed with computational efficiency optimization, achieving thorough component depiction while maintaining feasible element quantities [11]. Parametric investigations employing validated CFD frameworks examined viscosity and velocity impacts on gearbox fluid behavior [12]. Alternative computational methods using mesh-free particle hydrodynamics were subsequently benchmarked against traditional grid-based simulations using experimental PIV data [13]. Expanded parametric studies further examined viscosity-speed relationships in single-stage gears through finite-volume CFD modeling [14]. Integrated thermal-fluid simulations merging RNG k-ε turbulence modeling with dynamic meshing techniques provided comprehensive analysis of gearbox temperature fields, specifically evaluating rotational speed, lubricant level, and viscosity effects [15]. Subsequent work developed injection lubrication models to evaluate parameter impacts on oil distribution patterns within gear systems [16]. Experimental validation procedures were established to analyze lubricant flow through different oil delivery component geometries [17]. Advanced coupling approaches incorporating overset grid techniques enabled multiphysics analysis of thermal-stress-fluid interactions in lubricated gears [18]. Numerical studies identified optimal immersion depths for efficient gear lubrication and cooling [19]. Recent innovations include aerodynamic loss minimization studies using shrouded spiral bevel gear arrangements analyzed via multi-reference frame CFD [20]. Specialized lubrication models integrating finite-element-derived boundary conditions were created for single-tooth engagement analysis [21]. Particle-based simulation techniques were applied to simplified high-speed EMU gearbox models [22], and comprehensive heat transfer models were developed for monorail transmission systems [23]. The multiphase volume of fluid (VOF) approach was implemented to model internal oil flow within this motor [24]. A shroud design was implemented to encapsulate the high-speed unmeshed spiral bevel gear. Utilizing CFD software and a multi-reference frame approach, the windage characteristics of the proposed model were assessed against an unshrouded configuration, and the effect of bevel gear rotational speed on windage power loss was examined [25]. A CFD-based numerical methodology was introduced for predicting lubricant flows and power losses in gearboxes; this approach employed a meshing strategy reducing computational demands and facilitating parametric studies [26]. To mitigate power losses, a CFD simulation technique analyzing oil churning and windage losses was developed, leading to enhancements in the shrouds of high-loss bevel gears within gearboxes [27]. A pioneering numerical simulation model of the flow field in a gearbox featuring an oil volume adjustment device was created to investigate its effect on the lubrication properties of a high-speed electric multiple unit [28]. The stiffness load ratio between a cracked tooth and adjacent teeth was derived to analyze the temperature distribution in a cracked gear transmission system [29]. Based on thermal analysis, a numerical method integrating a mixed elasto-hydrodynamic lubrication model with the finite element method was proposed [30]. In order to solve the vibration problem of gear pump caused by flow field and compensation force, the high-speed cycloidal gear pump was taken as the research object, the effects of flow field temperature and radial compensation force of sliding bearing on the rotor performance were analyzed [31]. Considering the temperature significantly influences the elastic modulus of polymer gears, the impact of temperature on the lubrication characteristics of polymer gears was investigated [32]. To simulate the meshing state of gear teeth under actual working conditions, the flow field model of gear meshing process was established based on the multiphase flow model and the dynamic mesh method [33]. In order to improve the service performance of aviation gear pairs by using surface texture, a three-dimensional line contact TEHL model to conduct numerical analysis on spur gears with surface textures was employed and the influence mechanisms of circular dimple geometric parameters and non-circular textures on gear lubrication performance was investigated.

To study the internal flow field of the gearbox at different gear speeds, a computational model for the fluid in the gearbox is established. This model is used to analyze the distribution of gear oil as well as the changes in oil pressure and flow rate, thereby laying a foundation for the study of gear lubrication and cooling. Furthermore, to study the heating problem of the gearbox, a fluid calculation model for the gear pair and the box body is established. A unidirectional steady - state thermal - fluid - structure coupling analysis is conducted on the constructed three - dimensional model. During the simulation, with lubricating oil as the heat source, its transfer process between the gear and the box is studied through precise heat conduction simulation. Meanwhile, the thermal physical properties of gear materials, such as thermal conductivity, specific heat capacity, and thermal expansion coefficient, are fully considered, and the thermal stress and deformation of gears under thermal load are studied. Overall, the research work in this article is of important theoretical significance and engineering application value.

II. Material and Methods

1. System Parameters

In the helicopter tail gearbox, the performance of spiral bevel gears is crucial for the efficiency and reliability of the entire transmission system. In the design of these gears, their geometric parameters play a crucial role as they directly determine the load-bearing capacity, wear rate, and thermal stress distribution. This section will discuss in detail the basic parameters of spiral bevel gears used for modeling, which will lay the foundation for the subsequent thermal-fluid-structure coupling analysis. Table 1 lists a group of gear parameters based on a practical helicopter tail reducer, and Table 2 lists the mechanical properties of the gear material.

Table 1. Gear parameter

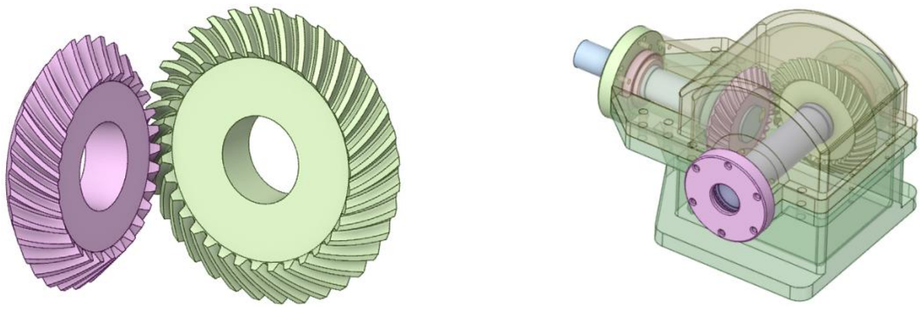
Item	Tooth number	Modulus (mm)	Pressure angle (degree)	Helical angle (degree)	Gear width (mm)
Driving gear	29	5.6	20	35	33
Passive gear	35				

Table 2. Parameters of gear material

Parameter	Value
Density (kg·m^{-3})	7890
Yield Stress (MPa)	360
Ultimate strength (MPa)	650
Tangent modulus (GPa)	210
Young modulus (N.m^{-2})	2.09 x 10^{11}
Poisson's ratio	0.269
Thermal conductivity (W·(m·K)$^{-1}$)	48
Specific heat (J·(kg·K)$^{-1}$)	450
Thermal expansion coefficient/kg^{-1}	1.17 x 10^{-5}

2. Gear System Physical Model

Based on the parameters set above, the 3D models of drive gear, passive gear and reducer assembly are established, as shown in Figure 1. Besides, the mechanical properties of gears are set accordingly.



(a) (b)

Fig. 1. 3D model of helicopter tail reducer: (a) Gear assembly; (b) Gear reducer assembly

The method includes research chronological, including research design, research procedure (in the form of algorithms, Pseudocode, or other), instruments, and analysis techniques used in solving problems. Experimental methods should be given in sufficient detail to allow these to be replicated by other researchers. Where possible, the source of the various reagents and materials used in the study should be given.

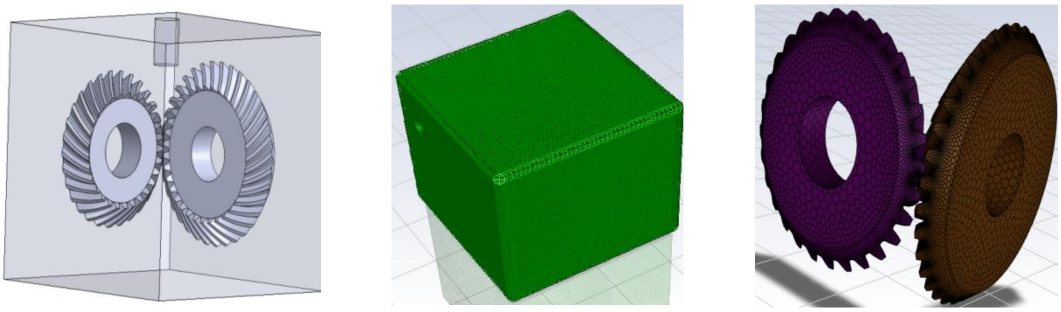
III. Results and Discussions

1. Unidirectional Steady State Heat-Fluid-Structure Coupling Analysis

In this section, the control variable method is utilized to analyze the influence of the parameters, and the ANSYS/fluent software is adopted. Due to the model's geometric complexity, tetrahedral elements were employed. To balance computational efficiency with solution accuracy, a mesh sensitivity study was performed. Based on this analysis, a global element size of 2mm was selected, as it achieved solution convergence; further mesh refinement yielded no significant improvement. Additionally, the mesh at the fluid-structure interface was locally refined to enhance accuracy. Finally, the frictional contact between gears is defined and the friction coefficient is set to be 0.02.

It should be noted that in the analysis of unidirectional steady-state thermal fluid-structure coupling, it is assumed that the interaction between the solid structure and the fluid is unidirectional. That is, the influence of the fluid flow and temperature distribution on the solid structure is one-way, while the influence of the deformation and stress distribution of the solid structure on the fluid flow is ignored. This assumption is reasonable in certain situations. Therefore, when performing unidirectional steady-state thermal fluid-structure coupling analysis, it is necessary to carefully consider the applicability and limitations of this assumption. According to the actual application situation, the lubricating oil temperature is set at 70 ˚C, the ambient temperature is set at 25 ˚C, and the small-gear speed is 245rad/s.

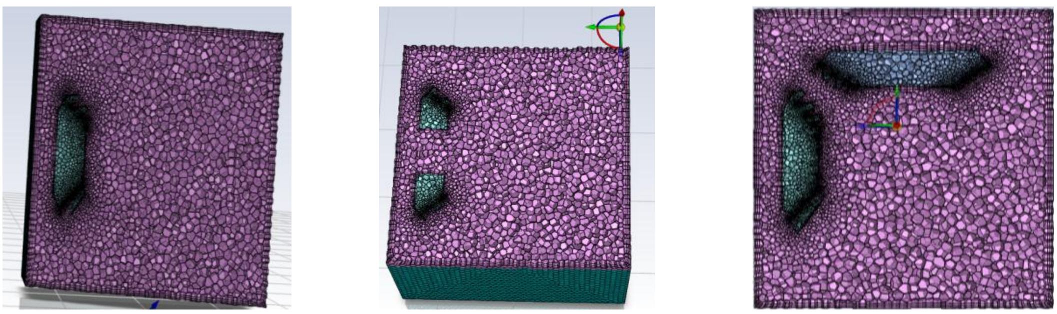
Firstly, a 3D geometric model is created and imported, and then it is appropriately simplified. After the processing of the gear model is completed, the cutting of the fluid region starts. In order to ensure the continuity of the mesh at the interface between the gear mesh and the hydraulic oil mesh, so that temperature and other data can be transmitted normally, the interface between the gear and the flow field is shared and connected. The simplified model is shown in Figure 2.



(a) (b) (c)

Fig. 2. Model processing: (a) Simplified gear reducer; (b) Meshing of fluid; (c) Meshing of gear

Based on the above-mentioned setting, the system meshing involving fluid and spiral bevel gears is obtained as shown in Figure 3. Additionally, the properties of the lubricating oil are set in Table 3.



(a) (b) (c)

Fig. 3. System meshing: (a) X direction; (b) Y direction; (c) Z direction

Table 3. Lubricating oil parameters

Parameter	Value
Density/(kg·m-3)	870
Specific heat/(J·(kg·K)-1)	2077
Thermal conductivity/(W·(m·K)-1)	0.1454
Dynamic viscosity/(kg·(m·s)-1)	0.087

According to the actual working conditions, the lubricating oil temperature is set to 70 ˚C, and the ambient temperature is set to 25 ˚C. The two gear flanks are at the junction of fluid and solid gears. One flank is for transferring the lubricating oil temperature to the gear, that is, for heat transfer between the gear and the external fluid. The other is for setting the speed, specifically for rotating and stirring the lubricating oil. Based on the actual situation, the wall speed of the small gear is set to 245rad/s, and that of the large gear is set to 203rad/s. After calculation, the surface pressure and speed clouds are obtained, as shown in Figure 4 and Figure 5 respectively. Similarly, the wall speed vector diagrams of the drive gear and the passive gear are obtained and presented in Fig.6, which shows the trajectory motion of the fluid stirred during gear rotation.

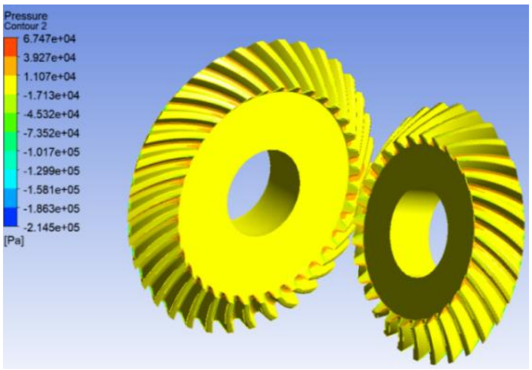


Fig. 4. Gear surface pressure cloud

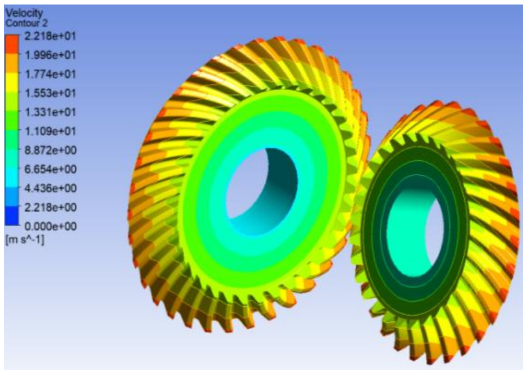
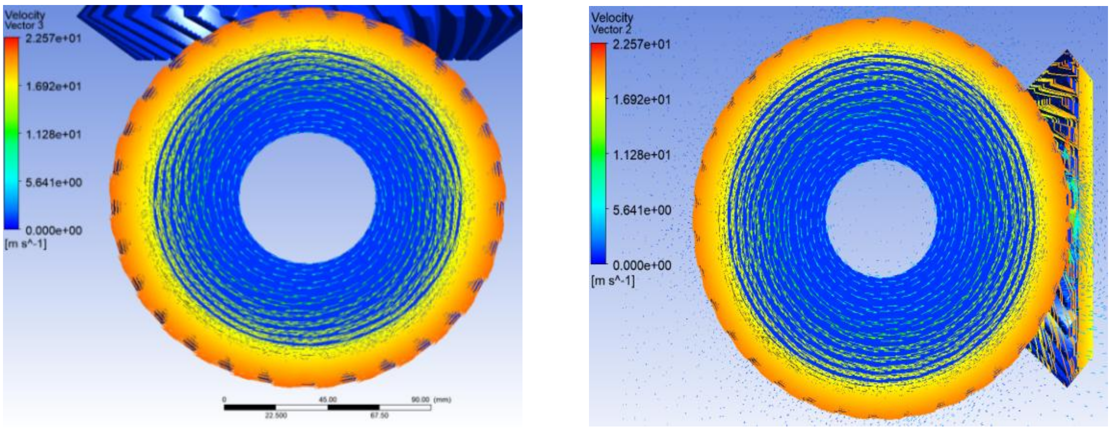


Fig. 5. Gear surface speed cloud



(a) (b)

Fig. 6. Gear wall speed vector diagram: (a) Drive gear wall speed vector diagram; (b) Passive gear wall speed vector diagram

Figure 7 and Figure 8 show the curves of gear speed and pressure change during the full-gear-width engagement. As can be seen from Figure 7, the speed increases significantly at first and decreases after reaching the maximum point. At the same time, from Figure 8, the pressure behaves inversely with that in Figure 7, which decreases quickly at first and increases after reaching the minimum value at the meshing point.

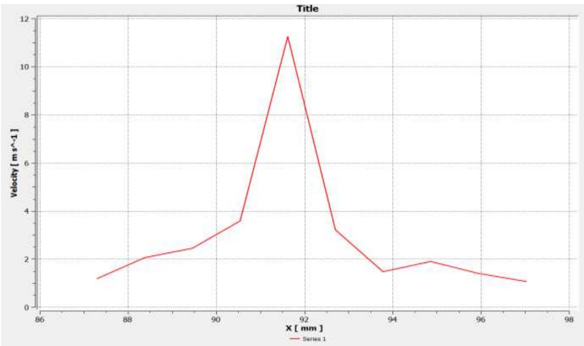


Fig. 7. Gear speed with the change of engagement

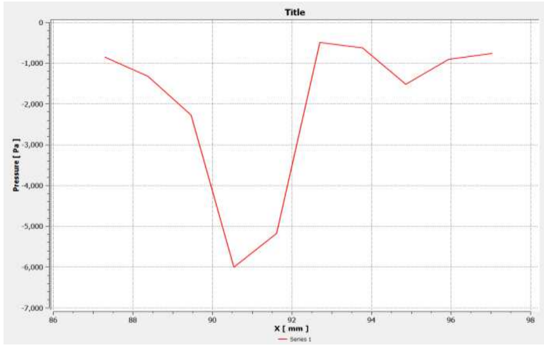


Fig. 8. Pressure curve with the change of engagement

Figure 9 to Figure 12 show the pressure cloud at different rotating speeds. Moreover, Figure 13 and Figure 14 respectively plot the maximum and minimum pressures at different speeds. It can be seen from Figure 13 that as the speed increases from 140rpm to 340 rpm, the maximum pressure on the gear surface rises about 4 times and reaches $1.25 \mathrm{x} 10^5$Pa. However, as shown in Figure 14, the minimum pressure decreases dramatically with the increase of the speed and reaches $-4 \mathrm{xx} 10^5$Pa when speed equals 340rpm.

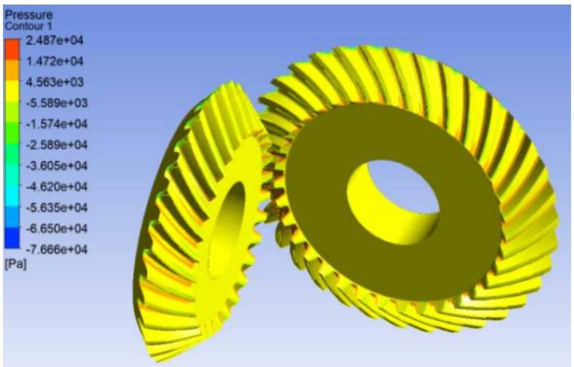


Fig. 9. Pressure when speed equals 140

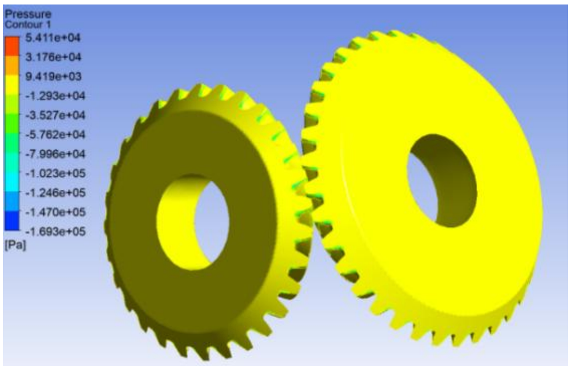


Fig. 10. Pressure when speed equals 210

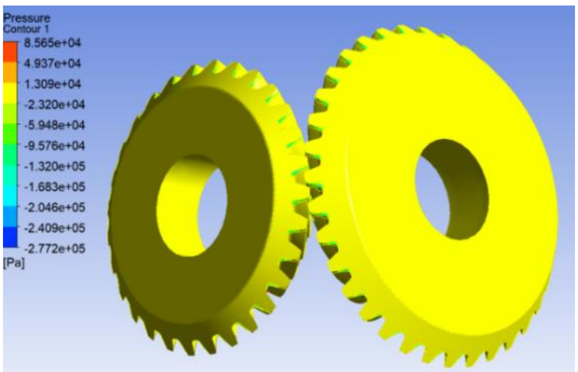


Fig. 11. Pressure when speed equals 280

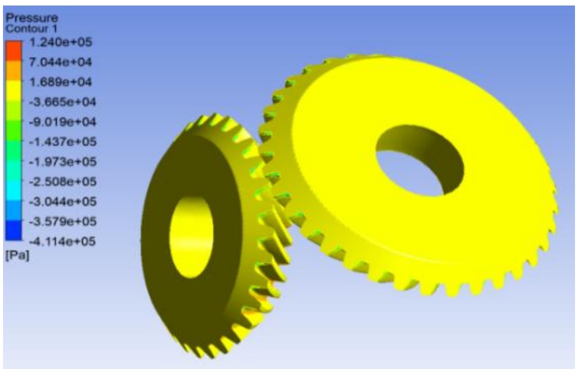


Fig. 12. Pressure when speed equals 350

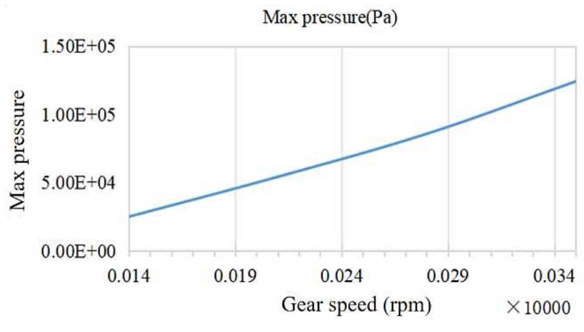


Fig.13. Maximum pressure under different speed

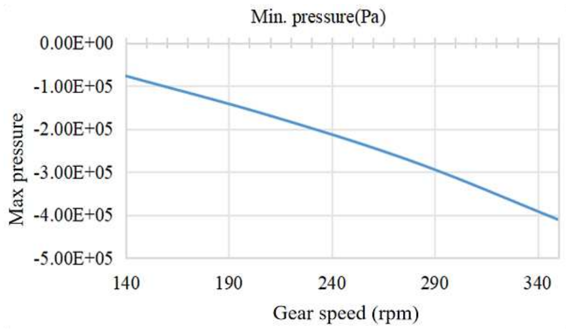


Fig. 14. Minimum pressure under different speed

2. Structure field analysis

The data of pressure, temperature, and other results calculated in Fluent will be mapped onto the gear wall surface in the structural field. Before the simulation, the gear material data need to be defined, and a non-linear plastic material is selected. Also, the system boundary condition is set. The starting temperature of the environment is 25 ˚C, the final working temperature is 70 ◦C, and the input torque of the driving gear is 200 Nm.

Figure 15 shows the grid diagram of the gear transmission structure. Moreover, through calculation, the deformation diagram and stress cloud diagram of the system structure are presented in Figure 16 and Figure 17, respectively. It should be noted that the stress and deformation distribution in Figure 16 and Figure 17 includes the effect caused by one-way heat-fluid coupling.

Fig.15. Meshing model

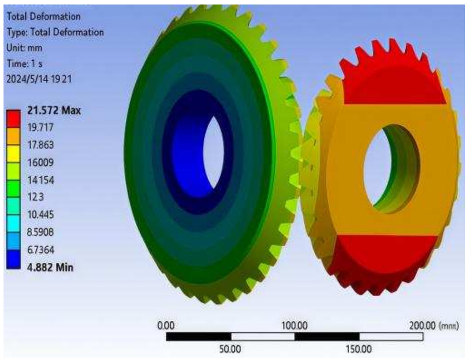


Fig.16. Deformation distribution

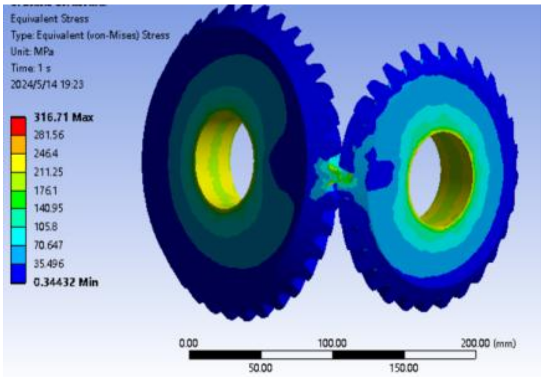
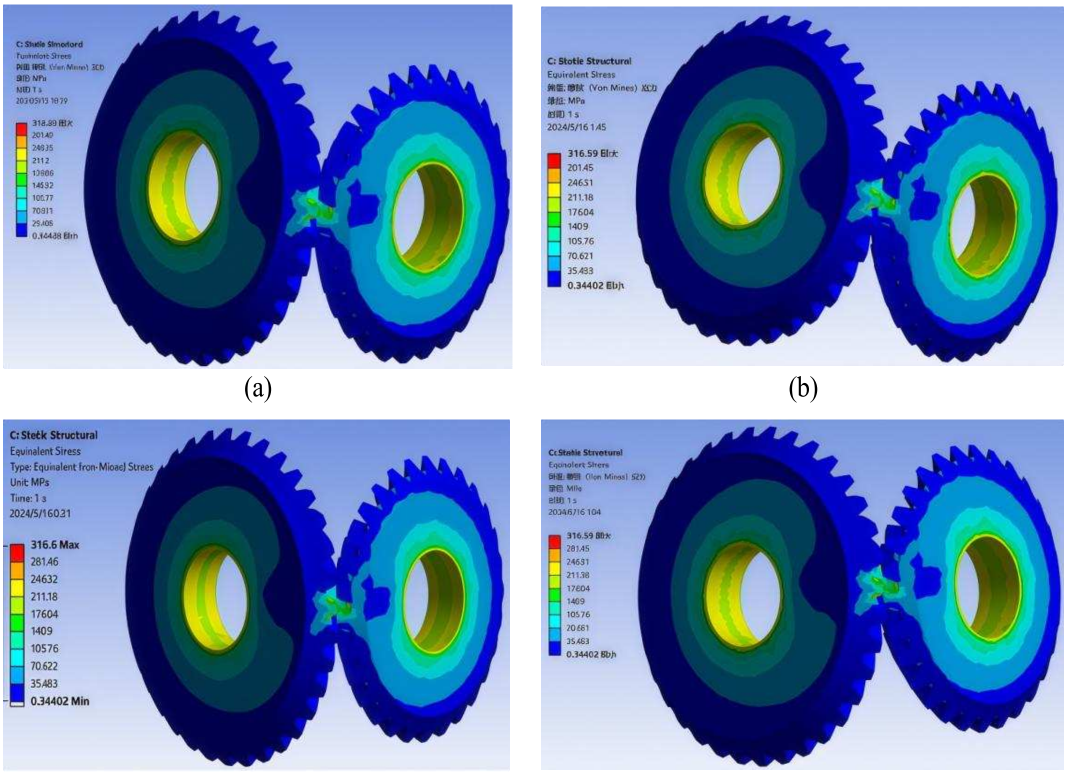


Fig. 17. Stress distribution

In order to obtain the stress distribution under the same input torque but different speeds, a set of parameters are set and the model is calculated. The stress distribution is shown in Figure 18. It can be found that, under different speed parameters, the maximum stress does not change significantly, indicating a weak dynamic effect.



(a) (b) (c) (d)

Fig. 18. Stress distribution under different speed: (a) 140rad/s; (b) 210rad/s; (c) 280rad/s; (d) 350rad/s

IV. Conclusions

Through in-depth research on the thermal-fluid structure coupling of the spiral bevel gear in the helicopter tail reduction gearbox, including unidirectional steady-state heat transfer, flow field simulation, and structural analysis, several aspects were revealed.

(1) Analysis indicates progressive acceleration of fluid velocity and pressure peaking at the meshing point. Concurrently, surface pressure polarization occurs with speed escalation - maximum contact pressure intensifies while minimum pressure attenuates. Flow field quantification demonstrates lubricant's dual-phase behavior, exhibiting both hydrodynamic transport and thermal regulation properties. Precise cooling effect measurement enables lubrication protocol refinement for thermal stress mitigation and heat dissipation enhancement.

(2) Static load simulations map stress concentration gradients and deformation patterns across gear teeth and housing assemblies. Besides, it is found that, under different speed parameters, the maximum stress does not change significantly, indicating a weak dynamic effect.

(3) Although the unidirectional steady state heat-fluid-structure researches are done in this paper, the dynamic analysis including transient coupling and harmonic response has not

been taken into consideration, and those dynamic coupling analysis as well as the experimental validation will be studied further in future schedule.

Acknowledgement

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