

Characteristics study of the gears by the CAD/CAE

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Abstract. Gears are the most important transmission component in machines. The rapid development of the machines in industry requires a shorter time of the analysis process. In traditional, the gears are analyzed by setting up the complete mathematical model firstly, considering the profile of cutter and coordinate systems relationship between the machine and the cutter. It is a really complex and time-consuming process. Recently, the CAD/CAE software is well developed and useful in the mechanical design. In this paper, the Autodesk Inventor® software is introduced to model the spherical gears firstly, and then the models can also be transferred into ANSYS Workbench for the finite element analysis. The proposed process in this paper is helpful to the engineers to speed up the analyzing process of gears in the design stage.

1. Introduction

Gears are the most important components in the transmission system. They can be cataloged into parallel, intersected, and crossed axes transmission. The theory of gearing proposed by Litvin [1] improves the studies and application in the gearing. Many papers were then published based on the application of the proposed theory [2-5]. Based on the proposed theory, the mathematical model of the generated gear is derived according to the equation of cutter and the generating mechanism. Complex processes and developed computer program are necessary to build up the analyzing tool. Recently, the development of CAD/CAE software makes the virtual manufacture becoming possible. Some of the researches are investigated based on the CAD/CAE sources. Chang et al. [6] applied the Solidworks API to simulate the shaving process of the gears. It reveals that the method can simulate the manufacture of gears efficiently. Wang et al. [7] applied the Inventor to simulate the manufacture of spherical gears. Based on the previous study, the virtual manufacture of spherical gears and worm gear set are investigated in this paper. It reveals that the gears generated by the CAD model becomes useful and efficient for the study of gears.



In the gear transmission, the assembly error is always existed to cause the transmission error in the transmission. In traditional theory of gearing, the tooth contact analysis is applied to study the contact ellipse and transmission error causing by the manufactured and assembly errors [1, 3]. The complex equations and non-linear equation solver are necessary to obtain the contact pattern and predict the kinematic errors. It limits the further study in the gears. Now, the well-developed CAD program can be a useful tool to help the engineers and researchers to understand the characteristics of gears through the virtual manufacture.

Spherical gear is a special type of gears which could be applied in the axes with angle variation. It can be divided into concave and convex shapes which are proposed by Mitome et al. [8]. The meshing of spherical gears can be cataloged into convex-convex, convex-concave, and convex-spur types in the intersected axes transmission as Fig. 1 shows [9]. Spherical gear pairs have small kinematic errors with axis misalignment [10] and avoid the edge contact as Fig. 2 shows [9]. Theory of gearing is successfully applied to build up the mathematical models of the spherical gears [10] and other gears [11-14]. However, the complicated deriving process and programming make the analysis difficult.

Worm and worm gear set is a kind of gear popularly applied in the crossed axes. The high gear ratio and ability of self-locking are the important characteristics. The contact between the worm and worm gear is very sensitive to the errors of manufacture and assembly [15-16]. Highly non-linear equations have to be solved by the numerical methods.

Now, the complicated tooth geometry can be successfully modeled by the CAD software and transferred to the CAE software for the further study. The investigated process is reasonable and efficient in the analysis of gears. However, the results need more verification in the near future to enhance the application of CAD/CAE in gearing.

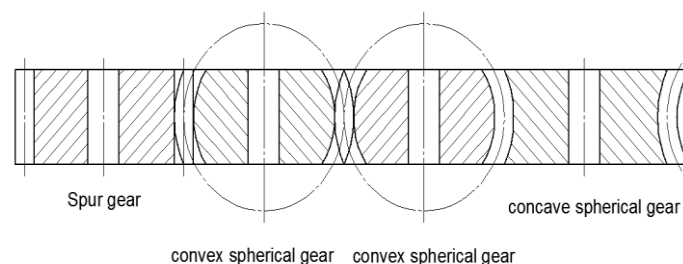


Figure 1. Different mating statuses of spherical gears [9]

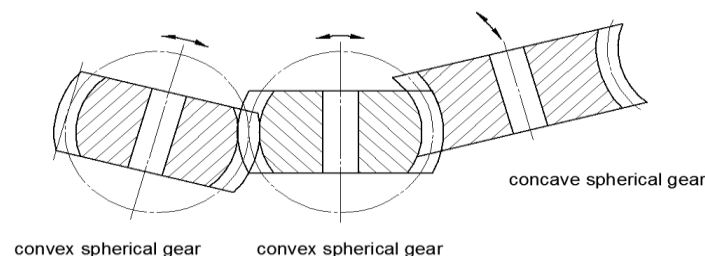


Figure 2. Spherical gear applied in the axis misalignment [9]

2. Solid models of the gears

Some kinds of CAD software are popularly applied in the geometry modeling, for example, Pro-E, Solidworks, and Inventor et al. The integration of CAD and CAE makes the software becoming powerful. The models can be transferred with each other for the further application. In this paper, the Autodesk Inventor is selected to build up the 3D solid models of the gears.

2.1 Model of the spherical gear [7]

The models of the gears can be set up by the derived equations obtained from the theory of gearing by simulating the manufacturing process. In order to avoid the complex deriving process, the simulation of the manufacturing process by CAD is applied in this paper to build the solid models of gears [7]. To build the solid model of spherical gear shown in Table 1, the processes are divided into (1) Setup the tooth profile of spur gear as the section of milling cutter; (2) Setup the gear-typed milling cutter; (3) Setup the raw material of the gear as Fig. 3 shows; (4) One tooth milling is preceded as Fig. 4 shows; (5) Complete the solid model of spherical gear.

The developed processes could be applied to generate different kinds of spherical gears with different spherical radius. Figure 5 and 6 show the convex and concave spherical gears.

Table 1. Fundamental data of the spherical gears

	<i>Pressure Angle</i>	<i>Module</i>	<i>Radius of Sphere</i>	<i>Number of Tooth</i>
Convex Spherical Gear	20 °	2.5 mm	100 mm	14
Concave Spherical Gear	20 °	2.5 mm	100 mm	14

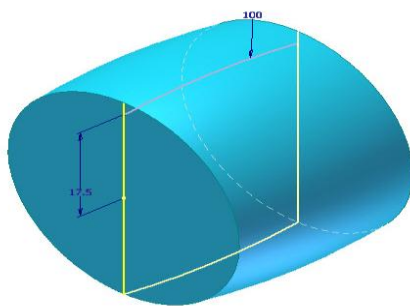


Figure 3. Raw material of a convex spherical gear

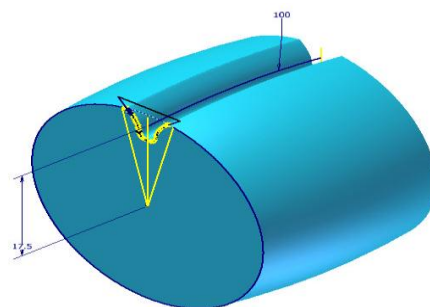


Figure 4. One tooth cut of the convex spherical gear

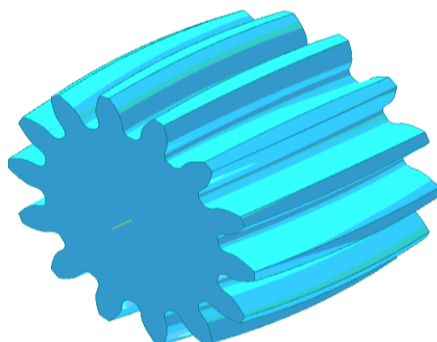


Figure 5. Convex spherical gear

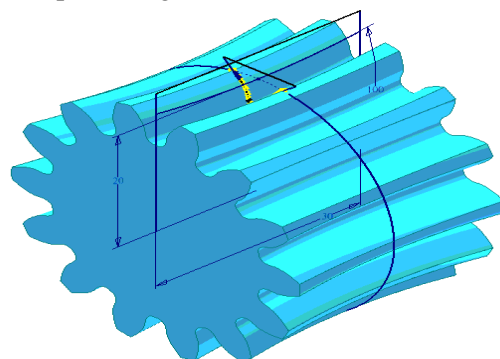


Figure 6. Concave spherical gear

2.2 Model of the Worm Gear

In the section 2.1, the models of spherical gears are simulated by the form cutter, i.e., milling cutter. There is no generation motion between the cutter and raw material. However, many kinds of gears' manufacture are based on the generation motion between the cutter and generated gears. The concept of inversed mechanism could be applied to simulate the generation process in CAD. In this section, the E-typed worm gear is illustrated to show the processes. The model of the E-typed worm could be set up

firstly by rotating the cutting edge along the axis of the worm shown in Fig. 7. The worm gear is then generated by the developed worm model. When the worm gear is manufactured by the worm-typed hob cutter, the rotation angle of the worm gear is according to the rotation angle of hob cutter divided by the gear ratio of worm gear set. In developing the CAD model, the worm gear could be considered as the fixed part while the worm model is rotating and swinging along the pitch circle of the worm gear. Fig. 8 shows the assembly of the developed worm gear set by the Inventor while the parameters of the worm gear set are shown in Table 2.

Table 2. Fundamental data of the worm gear set

	<i>Pressure Angle</i>	<i>Axial Module</i>	<i>Number of Tooth</i>	<i>Pitch Diameter</i>
Worm	20 °	3.0 mm	2	44 mm
Worm Gear	20 °	3.0 mm	30	90 mm

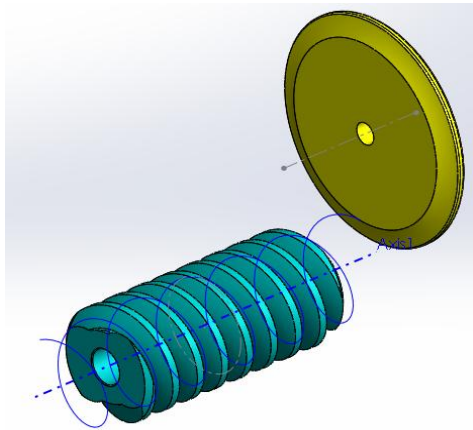


Figure 7. The model of the worm.

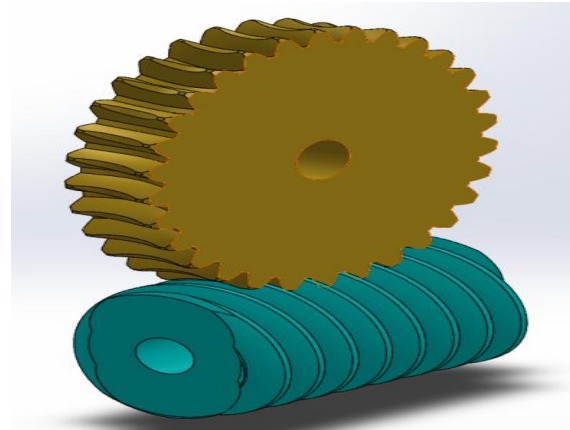


Figure 8. The assembly model of the worm gear set.

3. Stress analysis of the gears

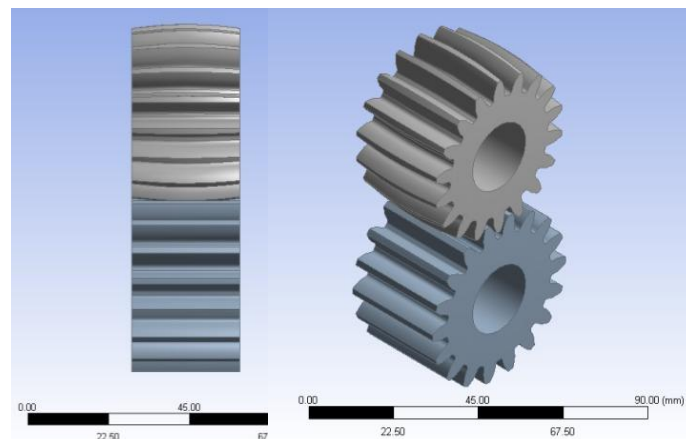
Nowadays, the CAD/CAE software is significantly improved and can be easily applied to predict the meshing conditions of the gears, especially, gears manufactured by the complex gear machining. The complicated mathematical model might be not necessary in developing the tooth profile. The developed models of the gears by CAD could be imported into the CAE for the further study.

Wang et al. [7] studied the stress analyses for the convex-convex and convex-concave combination of spherical gears. The results revealed that the convex-concave combination can have larger contact area and lower contact stress. However, from the view of manufacture, the combination of convex-spur might be another good choice in the application. Table 3 and Figure 9 show a convex spherical gear meshed with a spur gear in parallel, while the material properties are shown in Table 4. The input torque is set as 4 N-m. The contact areas of the gears are located near the middle region shown in Figure 10.

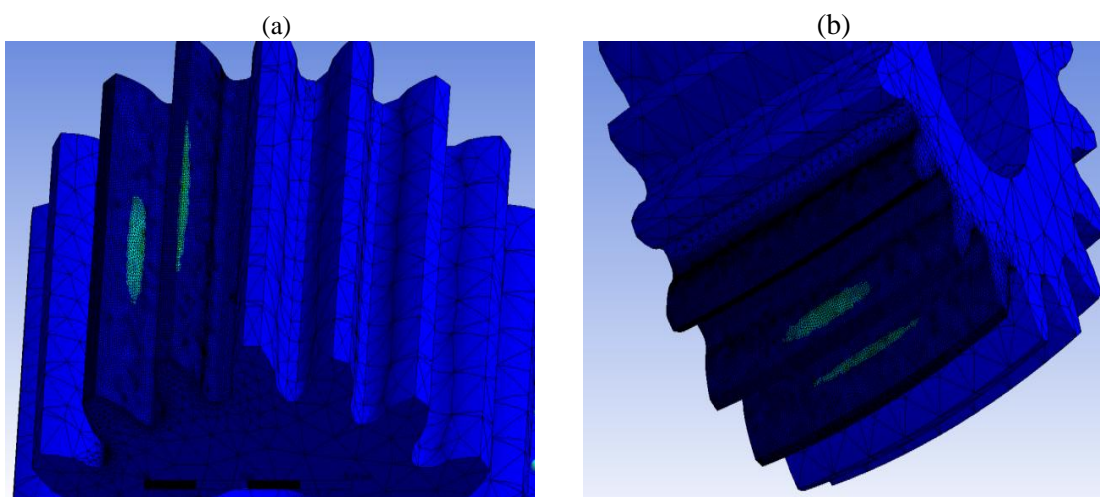
The important advantage of the spherical gear is good at the axes angle variation. It avoids the edge contact happened in the spur and helical gears. Figure 11 shows a convex spherical gear meshed with a spur gear in 10 degrees intersected. The contact areas of the gears are shifted away the middle region shown in Figure 12. However, it reduces the worst edge contact happened in the spur gear pair and helical gear pair.

Table 3. Parameters of 18-teethed gears

	Pressure angle	Module	Radius of sphere	Number of tooth
Convex spherical gear	20 °	2.5 mm	100 mm	18
Spur gear	20 °	2.5 mm	--	18

**Figure 9.** A convex spherical gear meshed with the spur gear in parallel**Table 4.** Material properties of the gears (Structure Steel)

Density	Young's modules	Possion's ratio	Tensile yield strength	Compressive yield strength
7850 kg / m ³	2E+11 Pa	0.3	2.5E+08 Pa	2.5E+08 Pa

**Figure 10.** Stress analysis (a) spur Gear; (b) convex spherical gear

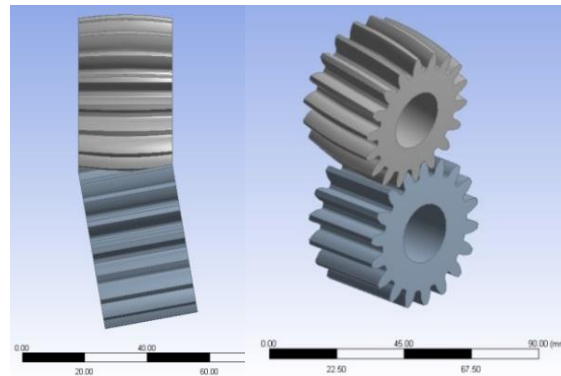


Figure 11. A convex spherical gear meshed with the spur gear in 10 degrees intersected

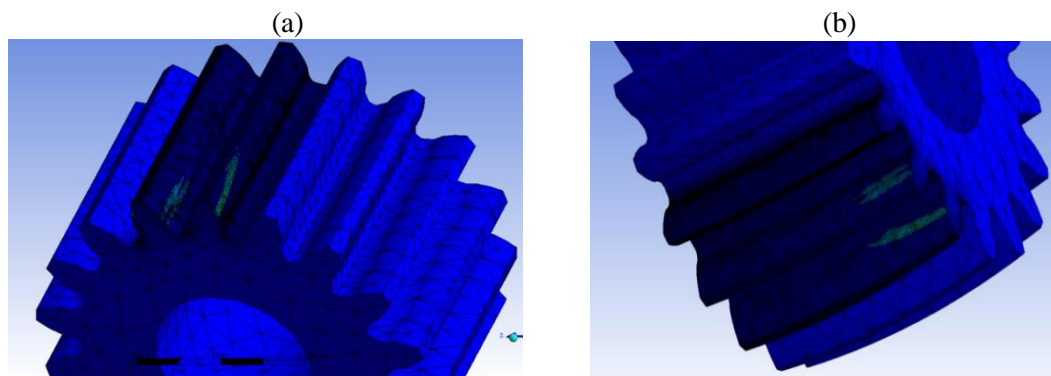


Figure 12. Stress analysis for 10 degrees intersected (a) spur Gear; (b) convex spherical gear

The mentioned process could also be applied in the study of the other types of gears. The worm gear set shown in Figure 8 is imported into the ANSYS for the stress analysis. Table 5 shows the properties of the materials while Figure 13 shows the stress obtained from the finite element analysis.

Table 5. Material properties of the gears

	Material	Density	Young's modules	Possion's ratio	Tensile yield strength	Compressive yield strength
Worm	Structural Steel	7850 kg / m ³	2E+11Pa	0.3	2.5E+08 Pa	2.5E+08 Pa
Worm Gear	Copper Alloy	8300 kg / m ³	1.1E+11Pa	0.34	2.8E+08 Pa	2.8E+08 Pa

4. Conclusions

The profiles of the gears are highly related to the manufacturing method and tools. The analysis of the gear meshing requires the development of the mathematical model of the profile firstly, considering the geometry of cutter and coordinate systems relationship between the machine and the cutter. It is a complex and time-consuming process for the engineer. Now, the CAD/CAE software is well developed and useful in the gear design and analysis. In this paper, the modeling and analysis processes are shown for the spherical gear and worm gear set. The models can be easily applied to predict the contact

between the gears considering different gears combination and assembly. It avoids the complex process in literature and speed up the design process in the gear transmission.

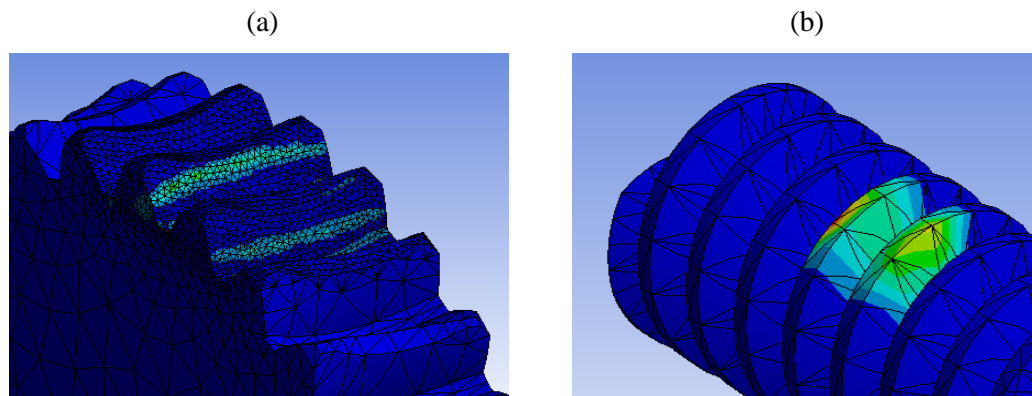


Figure 13. Stress analysis of the worm gear set (a) Worm Gear; (b) Worm

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