RomaxDesigner 의 사이클로이드의행기어 정밀분석
Precision Analysis on Cycloid Planetary Gear in RomaxDesigner

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Key words : Cycloid Reducer, Precision Transmission, Kinematic Analysis, Angular Transmission Error

1. Introduction

Cycloid planetary gear has been widely used in speed reduction and torque conversion in recent decades thanks to its advantages of high compactness, high reduction ratio, high torque capability and light weight comparing with other transmission drives. Precision transmission is the most important application (aerospace, robotics, point-positioning etc.) for cycloid drive, in which requires low backlash (less than 1 arcmin), high stiffness, and strict limitation for angular error. It is nevertheless difficult to achieve the goal owing to complex structure. [1, 2]

In this paper, we propose a mathematical model for precision analysis on cycloid planetary gear. The model has been embedded in sophisticated software RomaxDesigner as a module, which enable to consider manufacture tolerance, conduct pin contact analysis and investigate mesh stiffness and angular transmission error. Further, a 3D virtual model about RV transmission is built in RxD and relevant analyses are conducted with this approach.

2. Kinematic Analysis and Mathematical Model

For cycloidal transmissions under ideal conditions (without consideration for manufacture tolerance, system clearance and component deformation), half teeth of cycloid gear should be in contact with pins and sharing load. In practice, however, cycloid gear has unavoidable manufacture tolerance which could be intentionally controlled by various manufacture process. On one hand, this has advantages such as forming lubrication film, compensating heating expansion and reducing friction, pitting and scuffing. On other hand, this leads to backlash, angular transmission error and higher contact load which affect the accuracy and efficiency of transmission. Analysis on cycloid with tolerance is meaningful and critical.

Kinematic analysis on cycloid is shown in Figure.1. The tooth equation including manufacture tolerance is [3]

$$\begin{cases} x_c = \left[r_p + \Delta r_p - (r_{rp} + \Delta r_{rp}) S_r^{-\frac{1}{2}} \right] \cos\left[(1 - i^H)\varphi - \Delta\delta \right] \\ \quad - \dfrac{e}{r_p + \Delta r_p} \cdot \left[r_p + \Delta r_p - z_p (r_{rp} + \Delta r_{rp}) S_r^{-\frac{1}{2}} \right] \cos\left[(1 - i^H)\varphi + \Delta\delta \right] \\ y_c = \left[r_p + \Delta r_p - (r_{rp} + \Delta r_{rp}) S_r^{-\frac{1}{2}} \right] \sin\left[(1 - i^H)\varphi - \Delta\delta \right] \\ \quad + \dfrac{e}{r_p + \Delta r_p} \cdot \left[r_p + \Delta r_p - z_p (r_{rp} + \Delta r_{rp}) S_r^{-\frac{1}{2}} \right] \sin\left[(1 - i^H)\varphi + \Delta\delta \right] \end{cases} \quad (1)$$

in which, $i^H = \dfrac{z_p}{z_c} = \dfrac{z_p}{z_p - 1}$

$S_r = S_r^{'}(K_1, \varphi) = 1 - K_1^{'2} - 2K_1^{'2}\cos\varphi$

$K_1^{'} = e z_p / (r_p + \Delta r_p)$

Δr_p is pin pitch radius change

Δr_{rp} is pin radius change

$\Delta\delta$ is cycloid rotation change

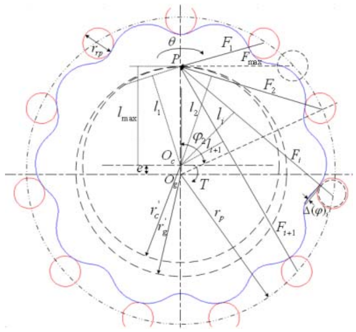

Figure.1 Schematic figure for the kinematic analysis

Initial clearance at i^{th} pin without elastic deformation:

$$\Delta(\varphi)_i = \min\left| \sqrt{(x_C - R_p \sin(\varphi_i - \theta))^2 + (y_C - R_p \cos(\varphi_i - \theta))^2} - r_p \right| \quad (2)$$

Here, θ is the angle change caused by combining manufacture tolerance which could be calculated with fixed $\Delta r_p \Delta r_{rp}$ $\Delta\delta$.

Distance between pin and cycloid gear profile at i^{th} could be expressed as

$$\delta_i = \frac{\sin(\varphi_i)}{\sqrt{1 + K_1^2 - 2K_1\cos(\varphi_i)}} \delta_{\max} \quad (3)$$

Here $\delta_{\max}$ is the function of maximum load on the pin

$$\delta_{\max} = f(L, \rho, r_p, r_{rp}, \nu, E) F_{\max} \quad (4)$$

Solution for $F_{\max}$ and $\delta_{\max}$ need an iterative process:

First give an initial force $F_{\max}^{(1)}$ which can be found without considering manufacture error, then calculate $\delta_{\max}^{(1)}$ from equation; after that apply for $\delta_{\max}^{(1)}$ calculating $F_{\max}^{(2)}$ from equation

$$F_{\max} = \frac{T}{\sum_{i=m}^{i=n} \left(\frac{l_i}{r_c^{'}} - \frac{\Delta(\varphi)_i}{\delta_{\max}} \right) l_i} \quad (5)$$

Go through iterative process, when $\left| F_{\max}^{(i)} - F_{\max}^{(i-1)} \right| < 1\% F_{\max}^{(i)}$, and then can stop iteration.

Meanwhile, pins in contact could be decided at same time with the criteria $\delta_i > \Delta(\varphi)_i$

Solution process has been embedded in RomaxDesigner which include stiffness and clearance of bearing, shaft and involute gear set as a system.

3. Study Example on RV Transmission

RV transmission is one of the typical applications of cycloid planetary gear, especially in industrial robotic. It has two stages transmission: planetary system with involutes gear set and pin-cycloidal reducing system with two cycloid discs (180 degree phasing difference). Configuration and 3D model in RxD is shown in Figure.2. All studies are focusing on cycloid mesh and effect from other components will not discuss here.

Load distribution Taking the manufacture tolerance into account, the load sharing among pins is investigated. One case study (input torque 100Nm, speed 2000rpm and manufacture tolerance $\Delta r_p = \Delta r_{rp} = 5um$). Result shows in Fiure.3.

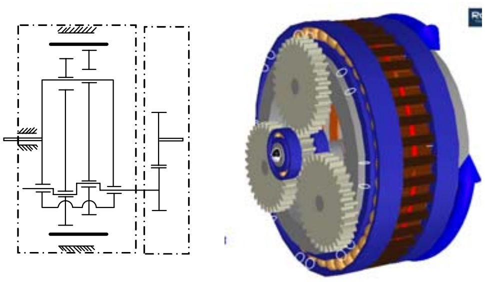

Figure.2 RV Transmission Structure and Model in RxD

Based on kinematic analysis maximum load occur when $\varphi_{\max} = \arccos(K_1)$. Here φ is distribute angle for pin, K_1 is accurate coefficient. In this study, 18 teeth are meshed for both disc and maximum load is on 15^{th}, 35^{th} pin respectively.

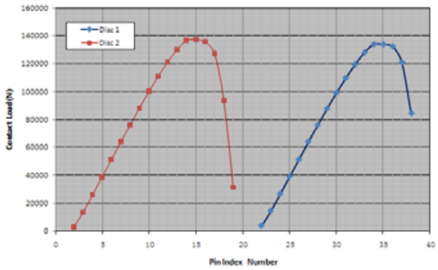

Figure.3 Load distribution on pins

Manufacture Tolerance Effect Transmission accuracy for cycloid system is tightly relied on manufacture tolerance. Figure.4 shows the rotate angle of cycloid disc along with torque under three cases (Case 1: $\Delta r_p = \Delta r_{rp} = 5um$; Case 2: $\Delta r_p = \Delta r_{rp} = 10um$; Case 3: $\Delta r_p = 10um, \Delta r_{rp} = 5um, \Delta\delta = 5arc\sec$). With slight torque close to zero, lag backlash [2] (he error in the actual position of the output shaft relative to its ideal position.) is calculated which varied from 40 to 80*arcsec*. It is helpful to check the effect of combination of different manufacture tolerance through discrepancy methods. Or setting backlash target first and searching optimized tolerance. Because of penetration between pin and cycloid tooth, disc will rotate while torque increase. Cycloid tooth mesh stiffness could be found consequently.

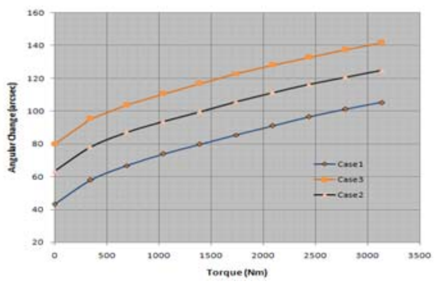

Figure.4 Disc rotation vs. torque

Angular Transmission Error It refers to a difference between the theoretical output revolution angle and the actual angle revolution angle when any revolution angle is the input, and is expressed as

$$\Delta\varphi_e = \Delta\varphi_{in} / i - \Delta\varphi_{out}$$

This is actually the gear ratio fluctuation once input speed is fixed. This kind of ripple is the major concern in practical applications. It is an unavoidable error from the eccentricity movement of crank shaft. Angular error result shows in Figure.5 which is the angular difference between input shaft and output shaft. It fluctuates along with input shaft rotating. The variation about 300*arcsec* implies the instability of the system which could cause any inaccurate positioning movement.

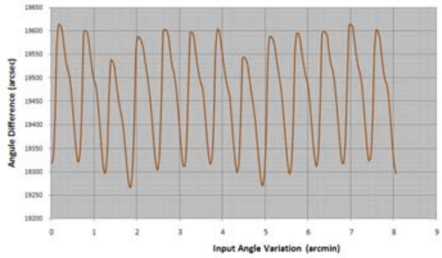

Figure.5 Angular Error (AE) vs. input shaft rotation

Angular transmission error is time variation, also changing with torque applied. Figure.6 shows the absolute value of AE increase with torque, which is mainly because of elastic deformation on system and clearance removing. The fluctuation increase also. However, the increase speeds is slow down for the reason that more pins are in mesh lead to higher mesh stiffness.

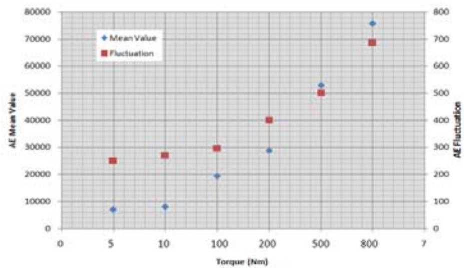

Figure.6 Angular Error (AE) vs. torque

4. Conclusions

We developed precision analysis approach for cycloidal planetary gear application. Kinematic analysis is carried out for building mathematical model. Model solution process is embedded in RomaxDesigner combining all components including involute gear, shaft and bearing as a system level solution. Example study is conducted on RV transmission for evaluating tolerance effect on performance. Angular transmission error is investigated on system level. Result shows this module is the effective tools for design and analysis on cycloid planetary gear.

Reference

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