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Linkage model and manufacturing process of shaping non-circular gears

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ABSTRACT

Current research of non-circular gear processing mainly focuses on gear hobbing. However, this method has many limitations including being unable to process internal gears or non-circular external gears with a concave pitch curve and is likely to undercut when processing non-circular gears of greater curvature with a smaller number of teeth. Gear shaping, in contrast, is a method that is able to overcome the limitations of gear hobbing. Relevant studies on gear shaping have focused on the theoretical bases rather than the concrete processes and tools. Through the combination of shaping theory and practice, this paper aimed to derive a linkage model for shaping non-circular gears, and to refine the feeding strategy, and develop a cutter retraction and cutter setting method. Finally, with a pair of 3-order sinusoidal-gear-ratio non-circular gears, this paper demonstrated the entire process in a CNC gear-shaping machine, thus proving the accuracy of the mathematical model and providing a valid reference for shaping non-circular gears.

1. Introduction

Due to their compact structure and accurate non-uniform transmissions, non-circular gears are widely used in function generators [1,2], gear pumps [3], and a variety of mechanical systems [4–6]. Until now, research on non-circular gears has been insufficient for their various categories, complicated shapes, complex design calculations, and especially their challenging manufacturing processes.

Many researchers have focused on the design of non-circular gears and their applications in mechanisms, but little attention has been paid to the processing aspects. Chen et al. [7] and Tan et al. [8] built a basic mathematical model for hobbing non-circular spur gears. Litvin, et al. [9] also built a model for hobbing non-circular helical gears. Liu et al. [10,11] and Xia et al. [12] constructed several hobbing systems and linkage models based on 4-axis and 5-axis hobbing machine respectively.

However, there are some limitations to hobbing non-circular gears, including the inability to process internal gears or non-circular external gears with concave pitch curves, and they are apt to undercut when processing non-circular gears of greater curvature variation and smaller number of teeth; fortunately, a more universal method that does not involve the above-mentioned limitations is available: gear shaping. Cheng et al. [13] built a basic mathematical model for shaping non-circular spur gears; Cheng et al. [14] and Bair [15] proposed a computerized tooth profile generation method and undercutting analysis method of noncircular gears manufactured with shaper cutter; Li et al. [16] proposed a numerical computing method of noncircular gear tooth profiles generated by shaper cutters; Tang et al. [17] discussed negative meshing in shaping non-circular internal gears;

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Xiong et al. [18] researched the avoid method of cutting interference in non-circular gear shaping. Unfortunately, there are no processing programs available for these models.

To solve these problems, this paper conducted the following exercises through a combination of shaping principles and manufacturing processes: a) Based on the normal vector of gear pitch curve, a simplified mathematical model of tooth profile-generating method with a shape cutter was established involving coordinate relationship, relative velocity, meshing equation, and b) in combination with the structure of the 3-axis linkage shaping machine and the process of shaping cylindrical gears, a mathematical model for shaping non-circular gears containing both a radial feed and rotary feed was developed. Furthermore, an equal-arc-length mathematical cutting model was proposed to avoid a varying cutting area in the model. c) A series of problems closely related to the process was discussed, including the feeding strategy, cutter-retracting approach, cutter preset method, and the design method of stock and fixture. d) A pair of non-circular gears with a 3-order sinusoidal gear ratio was then used as an example; the stock and corresponding fixture were designed, the processing parameters were set, the cutting process was simulated in the form of a computer graphic, and finally, the process was implemented with a 3-linkage CNC gear-shaping machine.

2. Mathematical model of generating noncircular gear

2.1. Generating method

Fig. 1 shows the geometric relationship of tooth-profile generating with a shape cutter. Its principle was to ensure the pure rotation between the pitch curve of a non-circular gear and the pitch circle of the shape cutter. Supposing that the shaped non-circular gear is fixed on the ground, the coordinate system $S_0(O_0 - x_0y_0)$ is rigidly connected to the gear. Its pitch curve is then defined as $r(\varphi)$. P represents the contact point between the pitch curve and pitch circle with a polar angle φ, thus:

$$\begin{cases} x_p = r(\varphi)\cos(\varphi) \\ y_p = r(\varphi)\sin(\varphi) \end{cases}. \tag{1}$$

Assuming that $\mathbf{t}$ is the unit tangent vector of the pitch curve, and according to the basic knowledge of the planar curve [19], the tangent vector at P can be found by:

$$\mathbf{t_0} = \begin{bmatrix} \dfrac{d(r(\varphi)\cos(\varphi))}{d\varphi} \\ \dfrac{d(r(\varphi)\sin(\varphi))}{d\varphi} \end{bmatrix} = \begin{bmatrix} r'(\varphi)\cos(\varphi) - r(\varphi)\sin(\varphi) \\ r'(\varphi)\sin(\varphi) + r(\varphi)\cos(\varphi) \end{bmatrix} \tag{2}$$

where $r'(\varphi) = \frac{dr(\varphi)}{d\varphi}$

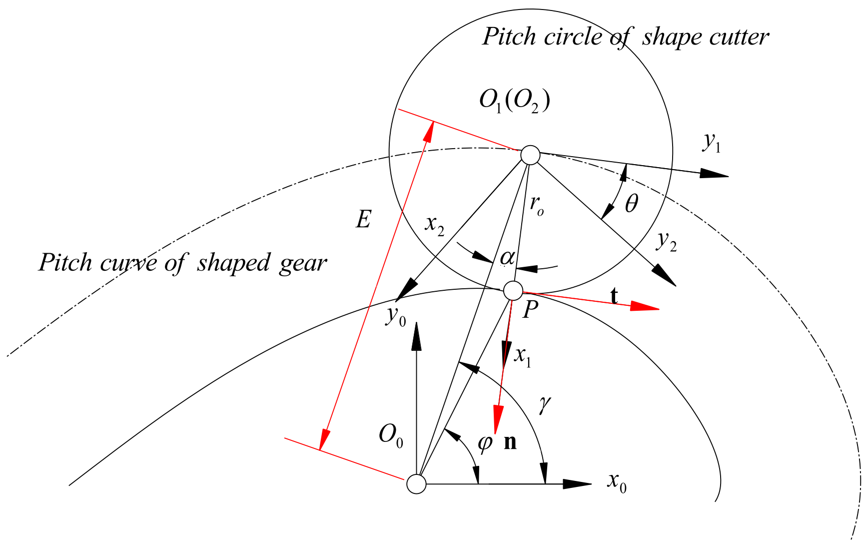

Fig. 1. Geometric relationships of tooth-profile generating.