Precise modeling of mould core for wavy lip seal

Modelización precisa del molde base para retenes de labio de sellado ondulado

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RESUMEN

- El retén de labio de sellado ondulado es un retén de presión dinámica con excelentes resultados de sellado. Sin embargo, establecer un modelo preciso para el molde base es extremadamente difícil por su irregular forma cilíndrica a causa del objetivo técnico para un labio de sellado ondulado con fabricación de precisión y análisis de resultados. Para resolver este problema se propone un método de modelización basado en el principio de transformación por desenrollado y enrollado circunferencial (CURT) para construir un modelo preciso de molde base. Se expone con detalle el principio CURT. Con esa base se presenta el método de modelización del molde base para retenes de labio de sellado ondulado. Finalmente se lleva a cabo un experimento de mecanizado del molde y análisis del error para verificar la aplicabilidad del método propuesto. Los resultados del análisis muestran que el máximo error del modelo es menor de 10^{-8} m. El experimento de mecanizado muestra también que el método es sencillo y efectivo, y que cumple completamente los requisitos de modelización de alta precisión para retenes de labio de sellado ondulado. La tecnología de modelización de alta precisión es la base para la fabricación y el análisis de resultados en retenes de labio de sellado ondulado. Especialmente, el principio CURT propuesto en este estudio puede ser utilizado también para resolver el problema de modelización y de fabricación por control numérico (NC) de otras piezas cilíndricas complejas. Las conclusiones muestran que el algoritmo propuesto no solo tiene alta precisión sino también alta versatilidad, que pueden compensar efectivamente los problemas de la actual tecnología en Computer Aided Design (CAD) y en Computer Aided Manufacturing (CAM) para el diseño y fabricación de piezas cilíndricas complejas.
- **Palabras clave:** Retén de labio de sellado ondulado, Molde base, Modelizado sólido, CURT, Transformación geométrica.

ABSTRACT

Wavy lip seal is a dynamic pressure seal with excellent sealing performance. However, establishing a precise model of the mould core is extremely difficult because of its irregular cylindrical shape resulting in the technical plight of the wavy lip seal in precision manufacturing and performance analysis. To solve this problem, a new method based on the principle of circumferential unwrapping and wrapping transformation (CUWT) was proposed to build the accurate model of the mould core. The CUWT principle was introduced in detail. Then, the modeling method of a mould core for wavy lip seals was presented. Finally, error analysis and machining experiment were carried out to verify the applicability of the proposed method. The results of the analysis show that the maximum error of the model is less than 10^{-5} mm. Machining experiment also shows that the method is simple and effective and that it fully meets the high modeling precision requirements for wavy lip seals. The high precision modeling technology lays the foundation for the manufacture and performance analysis of wavy lip seals. In particular, the CUWT principle proposed in this study can also be used to solve the problem of accurate modeling and the Numerical Control (NC) machining of other complex cylindrical parts. The conclusions show that the proposed algorithm not only has high precision, but also has a strong versatility, which can effectively compensate for the defects of the existing Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) technology in the design and manufacture of complex cylindrical parts.

Keywords: Wavy lip seal, Mould core, Solid modeling, CUWT, Geometric transformation.

1. INTRODUCTION

Lip seal is a hydrodynamic oil seal which is widely used in different industrial mechanical devices to prevent oil leakage for the good sealing performance [1,2]. Wavy lip seal is a special type of lip seal. After it is installed on the shaft, a wavy contact area is formed between the lip and the shaft, which increases the sweep width of the contact surface and the heat dissipation area. Compared with the common seal, the temperature and contact pressure in the contact area is reduced by 25-35%, and the escaping oil near the lip is pumped back to the oil chamber for the pressure gradient of the air side is greater than of the oil chamber, which effectively improves the working performance and increases service life of the wavy lip seal by at least 30% [3,4]. The sealing performance of the wavy lip seal mainly depends on the shape of the lip, and the lip surfaces of the wavy lip seal contains multiple complex free surfaces in the circumferential direction. Wavy lip seal is usually formed by moulding, thus the lip surfaces of the mould core should also be complex free surfaces in the circumferential direction. Essentially, the mould core of wavy lip seals is a complex column part with grooves and free-form surfaces in the circumferential direction. However, an accurate modeling of such parts is still a technical problem using the current technology in the field of Computer Aided Design (CAD) technology, leading to mould core which cannot be accurately machined, thereby restricting the wide application of the wavy lip seal. Hence, achieving an accurate model of the mould core must first be solved.

2. STATE OF THE ART

The precise modeling of the mould core of wavy lip seals is an urgent technical problem because of the accurate model of the wavy lip seal can not be effectively built with any commercial CAD software. However, there are a few researchs relate to wavy lip seals and its mould cores. Gautam et al. [5] analyzed the dynamic and static characteristics of wavy annular seals based on turbulent lubrication theory; however, these analyses did not consider the concrete structure and modeling problems of the oil seal and the mould, which were confined to theoretical derivation. Heo [6] and Dong [7] investigated wavy lip seal and mould core structures respectively, and applied for invention patents, while the accurate modeling and manufacture of the mould core were not involved. Zhu et al. [8] built a model to study the sealing performance for seals with sinusoidal waveform lip using SolidWorks software. However, the seal ring was an idealized and simplified model, and the modeling method was unsuitable for general wavy lip seals and their mould cores. The precise modeling of the mould core for wavy lip seals belongs to the modeling problems of the complex column part which includes grooves and free-form surfaces, and many scholars researched this problem. Scholars such as Kheifetc [9] proposed the algorithms of constructing the geometric model of gear drives and hob cutters, the model was gained in the algorithms after deduction of tooth from the blanks based on the technological process of manufacturing components, but the tooth of the mould core for wavy lip seals was difficult to create, so this method did not apply to the modeling of the mould core. Vijayaraghavan et al. [10] developed a CAD tool for the automated modeling of two-flute conical twist drills, and a solid model was created by the geometric and processing parameters of the two-flute conical twist drill, whereas this method was only effective on two-flute conical twist drills, and the method was not universal. Zhang et al. [11] built a model with higher precision of twist drills composed of standard spiral surfaces directly based on the grinding principle. This method was not universal as well. Islam et al. [12] studied the solid modeling method of spiral grinding wheels and developed a simulation program by Matlab. While the premise of this method was to establish a precise mathematical model of correlated surfaces, it was clear that the method was not applied to the mould core of wavy lip seals with complex free surfaces. Lyashkov et al. [13] and Nassef et al. [14] achieved the solid modeling of screws and rotary dental files, respectively, using a section scanning method in the CAD system, whereas the equations of cross-section contour or cross-section data models still needed to be addressed. In addition, Jiang et al. [15] derived a new modeling method for spatial cam in a limited slip differential mechanism. Skoczylas et al. [16] established the model and considered machining of worm thread. Dadalau et al. [17] actualized the parametric modeling of ball screw spindles in ANSYS. Kountanya et al. [18] discussed the three-dimensional parameterized geometric modeling of taper ball end mills. Pham et al [19,20] researched the geometric modeling of ball-end and end mills. However, the above-mentioned modeling methods which involved the surfaces of the parts were ordinary helical surfaces, so these methods were unsuitable for creating models for the mould core of wavy lip seals.

To accurately model mould cores for wavy lip seals, this study presents a circumferential unwrapping and wrapping transformation (CUWT) algorithm, which can transfer the solid modeling of columnar mould cores with complex grooves in the circumferential direction into the modeling of relatively simple mapping models (surface features lay on one side of a coordinate plane), and the accurate modeling of the mould core for wavy lip seals can be achieved using existing CAD technology. The mould core of the wavy lip seal can be precisely manufactured based on the mould core model, which make the bulk production of the wavy lip seal and the development of the seal industry to become a possibility. This method is also used to model the complex cylindrical parts with free surfaces precisely.

The rest of this study is organized as follows. Section 3 mainly introduces the theory and methods in this work and discusses the modeling method of the mould core of wavy oil seals. Section 4 builds a model of the four periodic sinusoidal mould cores and analyzes the accuracy of modeling and processing mould cores based on the model. Finally, the conclusions are summarized in Section 5.

3. METHODOLOGY

3.1. PRINCIPLE OF THE CUWT

The CUWT is a special transformation method for spatial cylindrical geometric models. Unwrapping and wrapping involve a pair of reversible transformations to obtain bidirectional transformations between complicated columnar parts with free surfaces and relatively simple mapping models. The basic principle of circumferential unwrapping is that a cylinder is cut by an axial section; the cylinder is then unrolled for a cuboid, and the length of the cuboid in the expanding direction is equal to the circumference of the cylinder that corresponds to reference radius R. The value of the reference radius R is a number greater than zero, which is chosen arbitrarily, and $R \in (0,+\infty)$. A radial section less than R is stretched, and a radial section greater than R is compressed in the mapping model of the columnar part. The principle of circumferential wrapping is opposite to that of circumferential unwrapping, thus, it can roll a cuboid to a cylinder. The key to the circumferential unwrapping and wrapping transformation is building the unwrapping and wrapping coordinate system (UWCS) and choosing reference radius R. Moreover, the UWCS and reference radius R of unwrapping transformation are the same as those of wrapping transformation.

The UWCS comprises of Cartesian coordinates o-xyz and column coordinates o'-$\rho\theta z'$ as is shown in Fig. 1. Cartesian coordinates o-xyz and column coordinates o'-$\rho\theta z'$ can be established based on the right-hand rule. In Cartesian coordinates o-xyz, the origin o is a point on the axis of a part, one radial direction of the part is the forward direction of the x axis, the z axis is to coincide with the axis of the part and the angle between the normal direction of the y axis and of the x axis is 90 degrees. At the same time, The z' axis and the origin o' of column coordinates o'-$\rho\theta z'$ coincide with the z axis and the origin o of Cartesian coordinates

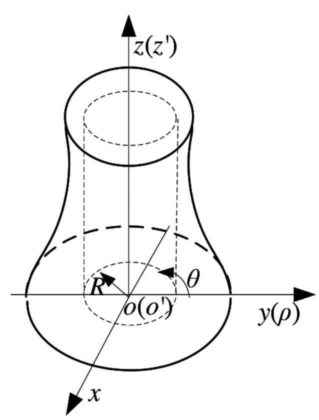

Fig. 1: Unwrapping and wrapping coordinate system

o-xyz, and the direction of the pole axis p is identical with that of the y axis. The polar angle θ rotates in a counter-clockwise direction, and $\theta \in [-\pi,\pi]$ in column coordinates o'-$\rho\theta z'$. The Cartesian coordinates *o-xyz* is the principal coordinates system, and the column coordinates o'-$\rho\theta z'$ is the auxiliary coordinates system in the UWCS. CUWT is in progress on Cartesian coordinates *o-xyz*. The aim of the column coordinates o'-$\rho\theta z'$ is to coordinate the conversion conveniently and simplify the calculation of columnar models.

In Fig. 1, R is usually one cylindrical radius of the columnar part, and $R \in (0,+\infty)$. Once R is selected, it does not change in circumferential unwrapping and wrapping transformation.

The CUWT of a columnar model consists of the CUWT of points, lines, and surfaces.

3.2. CUWT OF THE POINT

Point P is one point of a spatial columnar geometric model. As shown in Fig. 2, the UWCS and designate R should be initially set

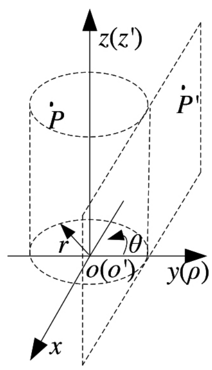

Fig. 2: CUWT of the point

up based on the methods described in Section 3.1. Fig. 2 displays the method of the CUWT for point P.

In Fig. 2, where r is the radius of a cylindrical surface that contains point P, the rectangular coordinates (x, y, z) and column coordinates (r, θ, z') of point P are presented in UWCS. Point P' is the expanding point of point P, and its rectangular coordinates can be expressed using (x_1, y_1, z_1). The rectangular coordinates (x_1, y_1, z_1) of unrolling point P' can be acquired by the formulas as is shown below:

$$\begin{cases} x_1 = -R\theta \\ y_1 = r \\ z_1 = z' \end{cases} \tag{1}$$

where $r \in (0,+\infty)$, $z' \in (-\infty,+\infty)$, $\theta \in [-\pi,\pi]$ and $R \in (0,+\infty)$.

The circumferential wrapping transformation of the point P' is achieved by solving the rectangular coordinates (x, y, z) of rolling point P using the rectangular coordinates (x_1, y_1, z_1) of unrolling point P'. To facilitate the calculation, the column coordinates (r, θ, z') of rolling point P can be counted by the rectangular coordinates (x_1, y_1, z_1) of unrolling point P' according to circumferential wrapping equation on column coordinates o'-$\rho\theta z'$:

$$\begin{cases} r = y_1 \\ \theta = -\dfrac{x_1}{R} \\ z' = z_1 \end{cases} \tag{2}$$

where $x_1 \in [-\pi R,\pi R]$, $y_1 \in (0,+\infty)$, $R \in (0,+\infty)$ and $z_1 \in (-\infty,+\infty)$.

The rectangular coordinates (x, y, z) of rolling point P are calculated using the column coordinates (r, θ, z') of rolling point P

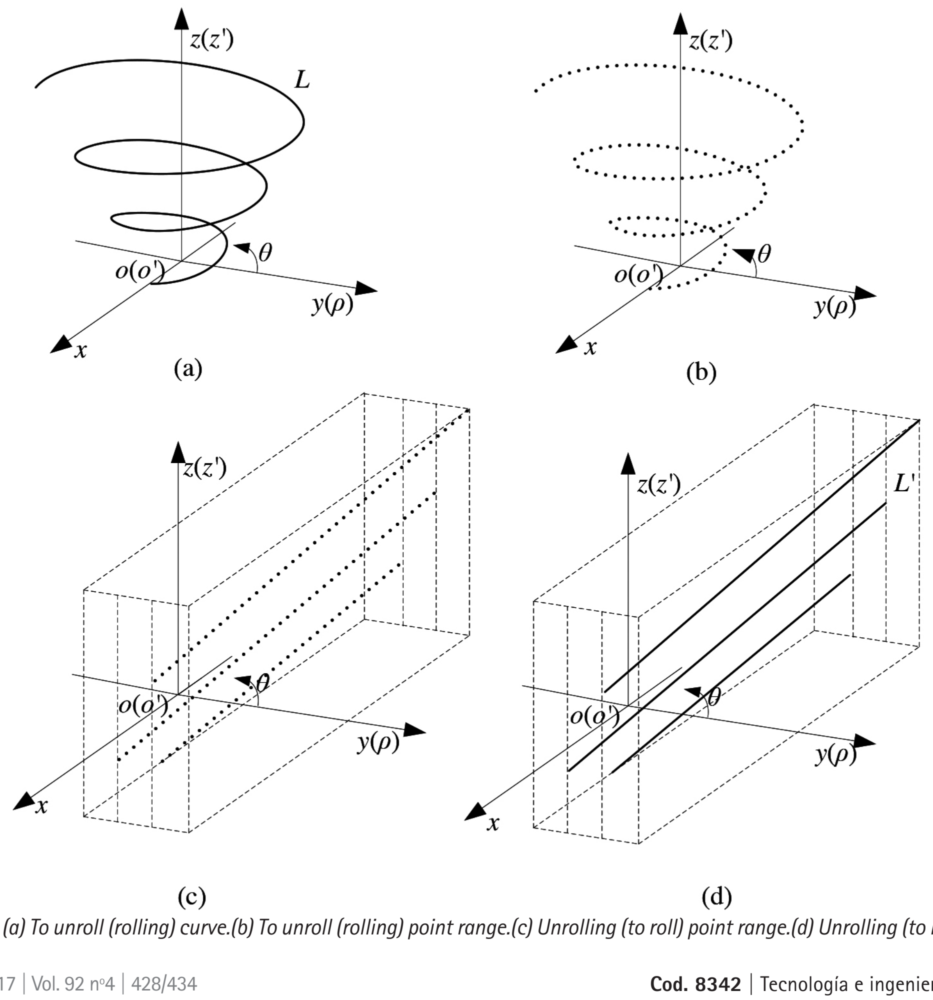

Fig. 3: CUWT of the curve. (a) To unroll (rolling) curve.(b) To unroll (rolling) point range.(c) Unrolling (to roll) point range.(d) Unrolling (to roll) curve

based on the conversion formula between rectangular coordinate and cylindrical coordinate:

$$\begin{cases} x = -r\sin\theta \\ y = r\cos\theta \\ z = z' \end{cases} \tag{3}$$

where $r \in (0, +\infty)$, $\theta \in [-\pi, \pi]$ and $z' \in (-\infty, +\infty)$.

3.3. CUWT OF THE LINE

Rolling curve L is one of the spatial curves as is shown in Fig. 3(a). The CUWT method for curve L is shown in Fig. 3. The method of the circumferential unwrapping of the line can be shown as below.

Firstly, UWCS is initially found as is shown in Fig. 3 and reference radius R is designated based on the method is presented in Section 3.1. Then, the rolling point range in Fig. 3(b) is acquired by uniformly taking points on the rolling curve L. Next, the unrolling point range is gained by unrolling every point in the rolling point range based on the methods described in Section 3.2 as is shown in Fig. 3(c). Finally, unrolling curve L' of curve L is built by interpolation by the unrolling point range based on the NURBS curve interpolation principle in Fig. 3(d) [21, 22].

Unwrapping and wrapping transformation of curves is a pair of reversible transformations when they have the same UWCS and R. To circumferentially roll curve L' in Fig. 3(d), unrolling curve L' is discretized into the point range, which is shown in Fig. 3(c), every point of the point range is rolled based on the circumferential wrapping algorithm, and the rolling point range is acquired in Fig. 3(b). As shown in Fig. 3(a), rolling curve L is found based on the NURBS curve interpolation principle. If unrolling and rolling of curves have different UWCS and R, the rolling curve does not coincide with the primary curve L.

3.4. CUWT OF THE SURFACE

Fig. 4 shows the CUWT process of the surface. Establishing UWCS and confirming the reference radius when unrolling the surface S as in Fig. 4(a) is important according to the method is proposed in Section 3.1. Then, the rolling surface lattice of the surface S is obtained by taking points on the rolling surface S in Fig. 4(b). To obtain the unrolling surface lattice in Fig. 4(c), each point of the rolling surface lattice is unrolled based on the methods described in Section 3.2. Unrolling surface lattice interpolates with the unrolling surface S' based on the NURBS surface interpolation principle [21, 23].

The unrolling and rolling of surfaces are reversible transformations when they have the same UWCS and R. To roll surface S' in Fig. 4(d), unrolling surface S' is discretized into the unrolling surface lattice as in Fig. 4(c). To obtain the rolling surface lattice in Fig. 4(b), each point of the surface lattice is rolled based on the methods described in Section 3.2 in Fig. 4(c). As shown in Fig. 4(a), the rolling surface S is found using rolling surface lattice based on the NURBS surface interpolation principle. As with the CUWT of the curve, if the unrolling and rolling of the surfaces have different UWCS and R, the rolling surface do not coincide with surface S.

The CUWT principle is also suitable for the Numerical Control (NC) tool path planning of complex column parts. First, the complex cylindrical part is transformed into a relatively simple mapping model by the CUWT method. Second, a 3-axis tool path planning for the mapping model is performed based on the existing Computer Aided Manufacturing (CAM) technology. Finally, the tool path for the 5-axis NC machining of the complex columnar part is gained by mapping all the cutter center points and cutter axis vectors of the 3-axis tool path according to the principle of circumferential wrapping transformation.

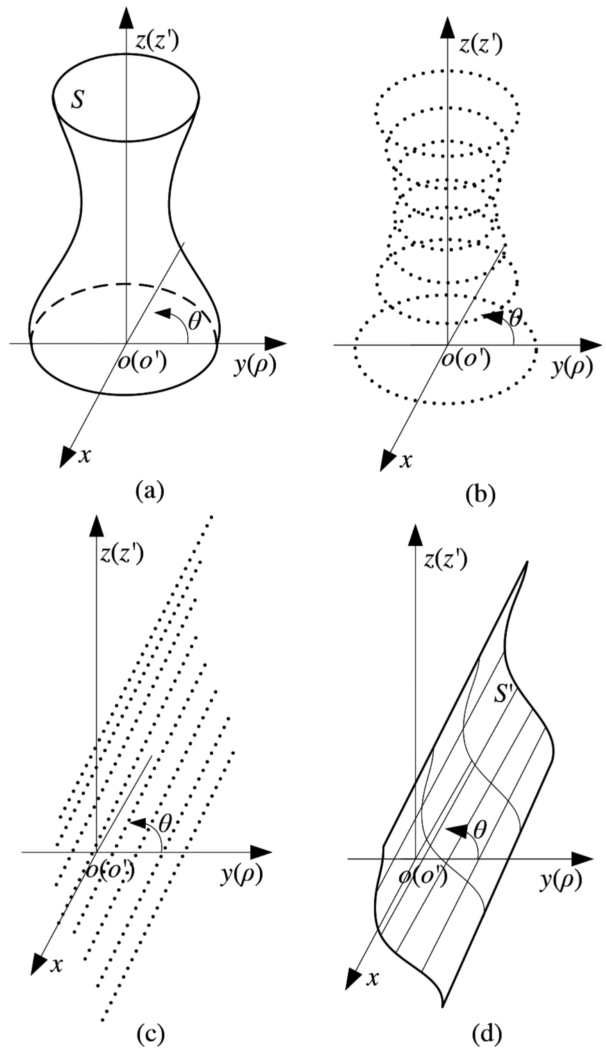

Fig. 4: CUWT of the surface. (a) To unroll (rolling) surface.(b) To unroll (rolling) surface lattice.(c) Unrolling (to roll) surface lattice.(d) Unrolling (to roll) surface

3.5. MODELING METHOD

The mould core of the wavy lip seal is formed by cylindrical surfaces, conical surfaces, circular planes, and ruled surfaces with boundary contours that are waveform curves in the circumferential direction, which is a typical complex columnar part. The existing modeling methods for the mould core of the wavy lip seal is a heavy workload and a time-consuming process, and modeling accuracy cannot be guaranteed. However, based on the circumferential unwrapping transformation principle, the mapping model of the mould core of the wavy lip seal is a simple model that is easy to model using existing CAD technology, and the mapping model is formed by rectangular planes and ruled surfaces with boundary contours that are plane wave curves. Therefore, this study builds the mapping model of the mould core firstly. Then all the surfaces of the mapping model are respectively rolled in the same coordinate system by rolling transformation. Finally, the solid model of the mould core is created by all the obtained rolling surfaces. The specific process is as follows.

The UWCS and designate reference radius R should be initially set up based on the method is presented in Section 3.1. The boundary contours of surfaces are represented by Eq. (4) in the mapping model of the mould core for the wavy lip seal:

$$\begin{cases} x = -R\theta \\ y = r \\ z = z_0 + A\varphi(\omega\theta) \end{cases} \tag{4}$$

where r is the cylindrical radius corresponding to the boundary curve, θ represents the polar angle of the point on the boundary curve in UWCS, $\theta \in [-\pi,\pi]$, reference radius R is a number which is chosen arbitrarily, and $R \in (0,+\infty)$, z_0 is the coordinate corresponding to the base line of the boundary wave curve, A is the amplitude of the curve, φ is the periodic function, and ω can be expressed as:

$$|\omega| = \frac{2\pi}{T} \tag{5}$$

where T is the period of the waveform curve. Furthermore, amplitude A is zero when boundary contours are straight lines.

The boundary contours of the unrolling model of the mould core which are generated to surfaces are found in the CAD software. The unrolling surface model of the mould core for wavy lip seals is shown as in Fig. 5 (see section: supplementary material). The unrolling surface model is stored in IGES file format, and all surfaces are NURBS surfaces in the IGES file.

Surfaces are sequentially read in IGES file format using the bespoke software that can read IGES files. An unrolling surface lattice is acquired by uniformly taking points on the unrolling surface based on the NURBS surface principle. Every point of the unrolling surface lattice is rolled based on the method described in Section 3.2 for rolling surface lattice. The rolling surface is set up by rolling surface lattice based on the NURBS surface interpolation method. Fig. 6 shows the procedure for modeling the lip surface on the air side.

All the surfaces of the mapping mould core model are rolled to closed surfaces, the result is shown in Fig. 7 (see section: supplementary material) based on the process of rolling the lip surface on the air side. To simplify the modeling process, the obtained closed surfaces are stored as a file in IGES format, which can be imported any one three-dimensional CAD modeling software to produce the solid model of the mould core using the solid modeling function of software.

4. SIMULATION ANALYSIS AND DISCUSSION

4.1. MODELING EXAMPLE

A solid model of the mould core for the four periodic sinusoidal lip seal as is shown in Fig. 8 (see section: supplementary material) is generated based on the modeling method of the mould core for random wavy lip seals is introduced in Section3.5. In Fig. 8, oil-side cylindrical surface (S_1), oil-side surface (S_2), air-side lip surface (S_3) and air-side surface (S_4) are formed by three circumferential wavy boundary contours and two circles, and amplitudes of wavy boundary contours are 0.1, 0.09, and 0.11 mm respectively. For ease of handling, the boundary curves of other surfaces are circles perpendicular to the mould core axis, and circles are regarded as four periodic sine curves which amplitudes are zero.

In Fig. 8, the main lip radius of the mould core is chosen to reference radius R, and R=16.6mm. The boundary contours of surfaces are represented in the unrolling model as follows:

$$\begin{cases} x = -R\theta \\ y = r \\ z = z_0 + A\sin(4\theta) \end{cases} \tag{6}$$

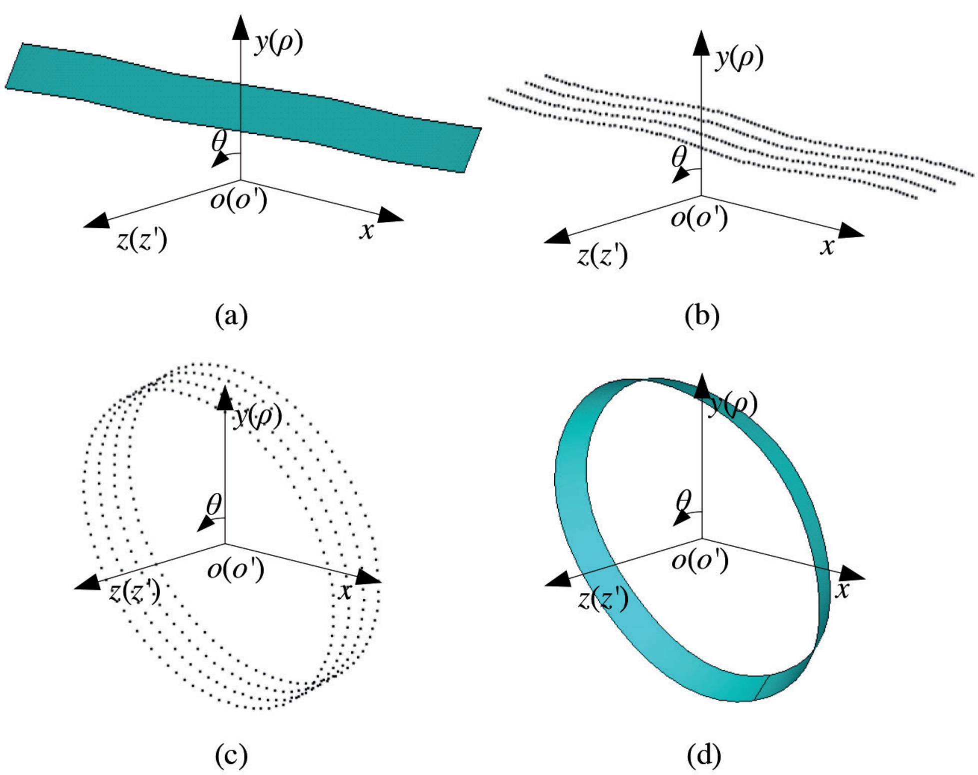

Fig. 6: CUWT of the lip surface on air side. (a) Unrolling lip surface on the air side.(b) Unrolling lip surface lattice on the air side.(c) Rolling lip surface lattice on the air side.(d) Rolling lip surface on the air side

In Eq. (6), where r represents the cylindrical radius corresponding to the boundary curve, θ is the polar angle of the point on the boundary curve, $\theta \in [-\pi, \pi]$, A is the amplitude and z_0 is the z coordinates corresponding to the base line of the boundary wave curve.

The unrolling surface model of the mould core is initially established based on the methods described in Section 3.5, and then, it is rolled to the entity model of the mould core by the rolling process, and the result is shown in Fig. 9 (see section: supplementary material).

4.2. ANALYSIS OF MODELING ACCURACY

The modeling accuracy of the mould core is analyzed to verify the validity of the method in this study. The error of the S_1, S_2, S_3 and S_4 are analyzed because the rest of surfaces of the mould core are cylindrical surfaces, conical surfaces, and circular planes. Taking the S_3 as an example, the error analysis method is illustrated as follows.

The surface lattice of the S_3 is calculated by using mathematical methods based on the structure of the S_3, and the lattice is recorded as the theoretical lattice. To analyze the deviation of the theoretical point to surface, a theoretical lattice and S_3 were imported to IMAGEWARE software. The contour map of the deviation is shown in Fig. 10.

In Fig. 10, the maximum deviation between the theoretical lattice and the S_3 is 7.184×10^{-5} mm. As shown in Table 1, the maximum deviations of S_1, S_2 and S_4 are gained by using the above method.

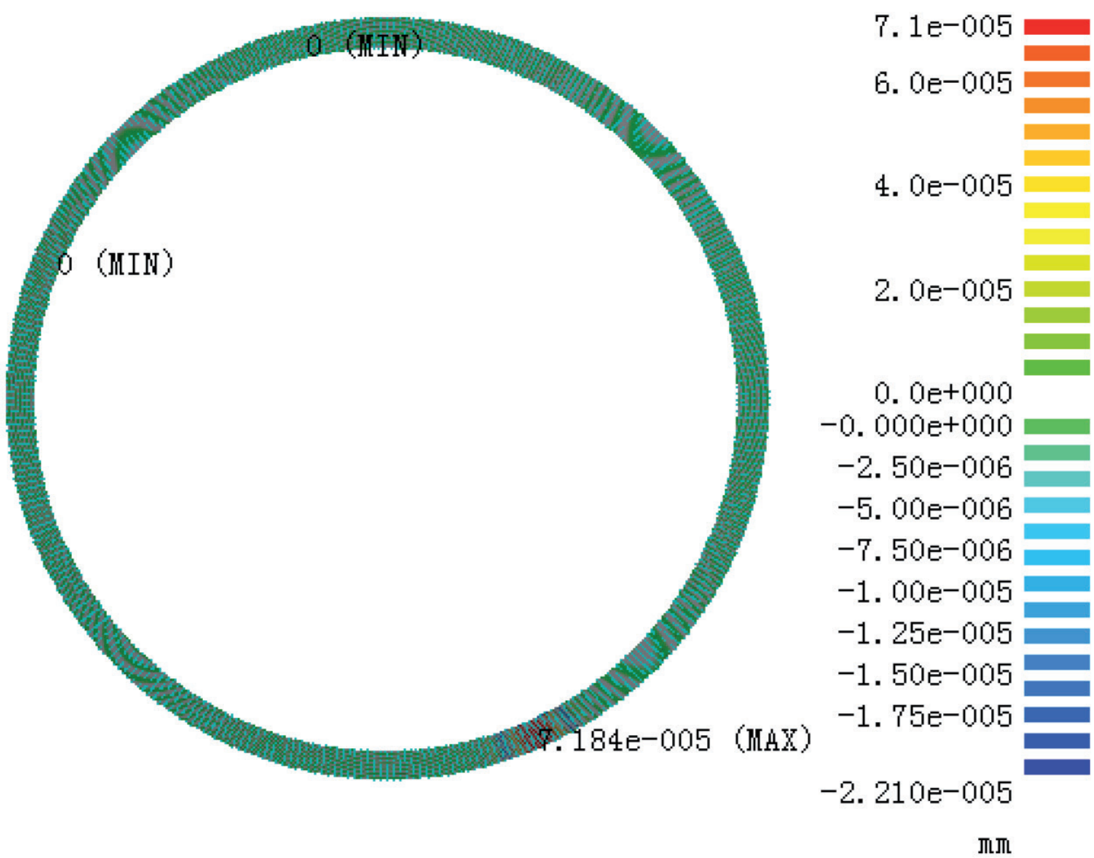

Fig. 10: Contour map of the deviation

Lip surfaces	The maximum deviation (mm)
Oil-side cylindrical surface	7.452×10^{-5}
Oil-side lip surface	5.41×10^{-5}
Air-side surface	6.924×10^{-5}

Table 1: Maximum deviation of lip surfaces

In Table 1, the error of the mould core model of the wavy lip seal is 10^{-5} mm, and it is extremely small. Thus, the method based on the CUWT has high modeling precision, which can fully meets the modeling accuracy requirements of the mould core in this study.

4.3. MACHINING INSTANCE

Based on the CUWT technology and the mould core model, the NC tool path planning for five-axis NC machining of the mould core is carried out in this study (not described in detail for brevity). Fig. 11 shows the artifactitious mould core photo. The proces-

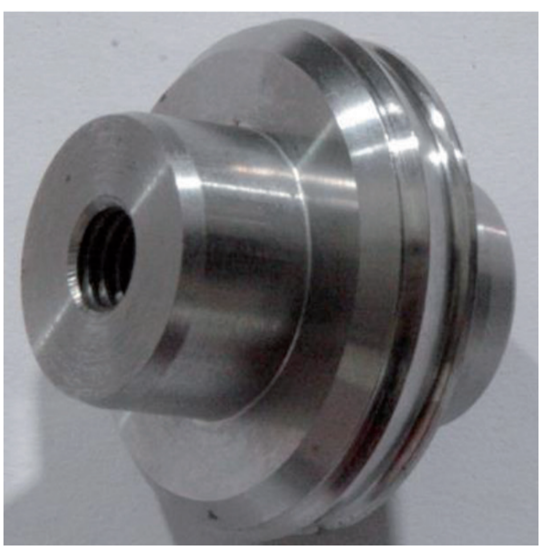

Fig. 11: Mould core of the four periodic sinusoidal oil seal

sing results show that the modeling method of the mould core for wavy lip seals is simple and effective.

5. CONCLUSIONS

Aiming at the technical problems existing in the modeling and manufacturing of the wavy lip seal, the CUWT principle and a novel precise modeling method based on the principle were presented in this study. The modeling accuracy of the mould core was then studied, and the machining precision of the mould core based on the model was analyzed. The following conclusions were obtained:

(1) Modeling problem of the mould core can be translated into the modeling of the relatively simple mapping model of the mould core based on the CUWT principle.

(2) The maximum modeling error of the mould core is less than 10^{-5} mm using the modeling method based on the CUWT technology.

(3) The modeling method proposed for the mould core of the wavy lip seal is also suitable for other complex cylindrical parts.

(4) CUWT theory proposed in this article can also be used to transform the 5-axis NC tool path planning of the complex cylindrical parts into the 3-axis NC tool path planning of the mapping model.

The modeling method based on the CUWT principle makes up for the defects of the existing CAD technology in the solid modeling of irregular cylindrical parts. However, the error analysis on modeling of cylindrical parts needs to calculate surface lattice by using mathematical methods, which may lead to calculation errors. This finding may be a key point of future research. The real error of the mould core for the wavy lip seal is due to the mould core manufacturing process and the mould core model, to compensate the error of the mould core manufacturing process is another point of future research.

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