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A Non-Ideal Geometry Based Prediction Approach of Fitting Performance and Leakage Characteristic of Precision Couplings

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ABSTRACT Since current studies on the leakage flow of precision couplings are based on the ideal smooth surface, neglecting the influence of geometric structures of machined surfaces, here we proposed a non-ideal geometry-based approach in this paper to perform a more accurate prediction on the fitting performance and the leakage characteristic of precision couplings. Firstly, a non-ideal geometric surface model of precision couplings is established by fractal function that characterizes both the dimensional discrepancy and the form error of key fitting surfaces, and theoretical calculation formulas based on the non-ideal geometric model are proposed afterward to predict the fitting performance and the leakage flow rate of precision couplings. Then, the influence of various factors on the leakage flow is also analyzed by the CFD approach. Simulation results and experimental results are compared to the theoretical calculation results, so the prediction approach proposed in this paper is verified to be feasible and accurate. Finally, the proposed approach is applied to the assembly analysis of spool valve of electro-hydraulic servo valve.

INDEX TERMS Annular clearance, dimensional discrepancy, fitting accuracy, form error, leakage flow.

I. INTRODUCTION

A great number of precision couplings exist in the hydraulic component such as precision electro-hydraulic servo valve and hydraulic pump, and there must be the fitting clearance between precision couplings for relative motion. For the spool valve of the electro-hydraulic servo valve which is constituted of the valve core and the valve sleeve, when there is pressure difference between the two ends of the clearance, or the wall surfaces of the clearance move relatively, the fluid flow in the clearance will cause leakage, directly influencing performance parameters of the electro-hydraulic servo valve such as control accuracy and frequency response characteristic. Because various characters of part surface will lead to various fitting accuracies of precision couplings, it is often verified by practical assembly whether the fitting accuracy can meet the demands of product performance, which influences the production efficiency. Therefore, refined calculation of the fitting clearance of precision couplings and prediction of the leakage flow rate caused by the fitting clearance have important significance for production and assembly of the hydraulic component such as precision electro-hydraulic servo valve and hydraulic pump.

At present, there are several researches on the leakage flow of precision couplings. Eryilmaz and Wilson [1] indicated that for precision positioning servo valves, the leakage flow between the valve core and the valve sleeve severely degrades the design performance of a hydraulic servo. An improved servo valve model was developed by experimental leakage flow data which combined both leakage and orifice flow. The combined model could also be easily parameterized using available manufacturer data. Gordić *et al.* [2] proposed several mathematical models for the calculation of the internal leakage flows based on the valve geometry and physical properties of working fluid. Comparing the simulation result with the corresponding experimental data, it was a good basis for predicting the behavior of axial spool valve in regimes close to spool zero position. Ruan *et al.* [3] established a stability criterion from a linearized model of the hydraulic valve and analyzed the effects of certain structural parameters on the valve's static and dynamic characteristics. Properties such as mechanical stiffness, leakage flow rate and dynamic response were obtained with different structural parameters and system pressures, and the influence of the leakage rate on the stability of a spool valve was analyzed. Goharrizi and Sepehri [4] analyzed external and internal leakages of a hydraulic actuator based on wavelet transform, and this method could be used to identify and isolate external and internal leakages without modeling the actuator or leakage types. Kövári [5] established an advanced nonlinear more realistic mathematical model and used step response analysis to examine the dynamic behavior of the electro-hydraulic servo system when internal cylinder's leakage resistance decreased. Simulation results showed the dynamic behavior of the system to assess the leakage effect. Zhou *et al.* [6] proposed a basic calculation method of leakage in the annular clearance under laminar and turbulent flow conditions, and analyzed the influence of the sloped axial, the move and rotation of the axial and the change of temperature and pressure on leakage. Strmcnik and Majdic [7] analyzed the leakage in the annular gap between the spool of hydraulic directional control valves and the hole channel in water and oil hydraulics separately, and it was shown that grooves with an unusually larger gap led to less leakage in the case of the hydraulic fluid with the lower viscosity. Xue [8] proposed a mathematical model of the fluid leakage in the gaps of the hydraulic system to analyze the influence of the pressure, the temperature and air bubbles. The relations of the leakage, the dynamic viscosity and the above factors were obtained by numerical simulation respectively. Zhou and Hao [9] studied the leakage characteristics under different outlet pressures and eccentricities. The experimental results showed that the leakage increases and efficiency decreases as the outlet pressure increases, and leakage increases as eccentricity increases. Zhao and Hao [10] analyzed the micro unit of the eccentric annular clearance, and established partial differential equations based on the law of Newton internal friction. The flux formula was obtained under concentric and eccentric conditions, which was applicable to both the concentric flow of thin clearance and the eccentric annular flow of large clearance.

In all the researches above, analytical solutions or numerical solutions of the leakage flow rate of a valve were obtained, but their calculation models were all based on the assumption that the fitting surfaces of the valve core and the valve sleeve were ideal cylindrical surfaces. Owing to the small size of precision couplings, it requires a high fitting accuracy that is around several microns, and the influence of micro geometric structures of practical machined surfaces of precision couplings on the leakage flow rate therefore cannot be neglected. For the spool valve, it can be considered that the valve surface is hydraulic smooth surface [11], and the roughness has little influence on the flow rate. As a result, the main component of geometric structures of a non-ideal fitting surface is the form error, which is mainly the cylindricity of the valve core and the valve sleeve. Fig. 1 shows the prediction process of the fitting performance and leakage flow rate of precision couplings. The major contribution of this paper is to provide a novel approach that considers both the dimensional discrepancy and the form error of precision couplings to obtain the influences of geometric structures on the fitting performance and various factors on the leakage characteristic through a non-ideal geometric model. The simulation results and experimental results show that the proposed prediction approach has high credibility.

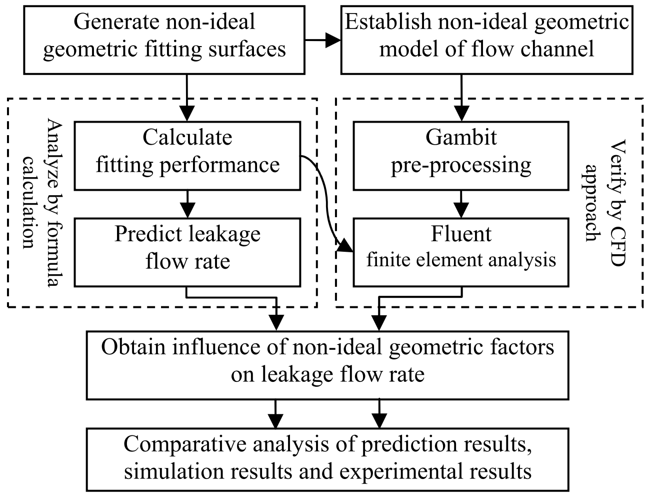


FIGURE 1. Process of performance prediction of precision couplings based on non-ideal geometry.

II. CONSTRUCTION OF NON-IDEAL GEOMETRIC FITTING SURFACES OF PRECISION COUPLINGS

Because the altitude variation of a machined surface of precision couplings is stochastic and statistically self-affine, the fractal theory has the superiority to describe the non-ideal micro structures of fitting surface at all scales without the restraint of resolution and sample length. Eq. (1) is the characteristic function of fractal surface altitude field [12], which is proposed to simulate the stochastic altitude distribution of a fitting surface of precision couplings in rectangular coordinate system.

$$
\begin{aligned}
z(x, y) &= L\left[\frac{\ln \gamma}{M}\right]^{\frac{1}{2}} \sum_{i=1}^{i_{\max}}\left[\frac{G_i}{L}\right]^{(D_i-2)} \\
&\times \sum_{m=1}^{M} \sum_{n=n_i}^{n_{i+1}} \gamma^{(D_i-3)n} \cdot \left\{\cos \phi_{m,n} - \cos\left[\frac{2\pi\gamma^n\left(x^2+y^2\right)^{\frac{1}{2}}}{L}\right.\right. \\
&\left.\left.\cos\left[\tan^{-1}\left(\frac{y}{x}\right)-\frac{\pi m}{M}\right]+\phi_{m,n}\right]\right\}
\end{aligned} \tag{1}
$$

where x and y are rectangular coordinate values of any point on the surface; result z is the altitude value; D_i and G_i represent the corresponding fractal dimension and fractal roughness in each spectrum region; L is the sampling length, including L_1(x direction) and L_2(y direction); D_i is the number of multi-fractal; γ is a scale parameter which controls the

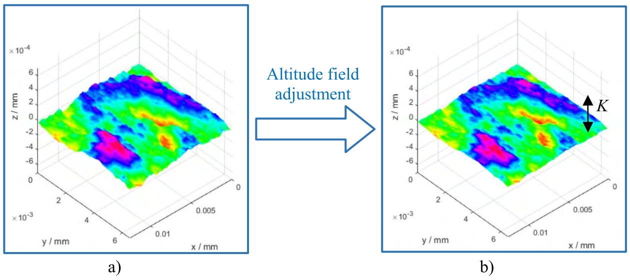


FIGURE 2. Altitude field adjustment of form error of fitting surface.

density of frequencies of the rough surface; M denotes the number of superposed ridges; n is the times of summation; $\phi_{m,n}$ is a stochastic phase in the interval $[0, 2\pi]$.

Taking the spool valve as an example, L_1 is the perimeter of the spool valve including the radial dimensional discrepancy, and L_2 is the axial length of the spool valve. The remaining parameters are determined by the processing method and cutting parameters of the spool valve. Then the calculated altitude data of the three-dimensional fractal surface is transformed into two-dimensional surface altitude field, and two-dimensional discrete wavelet analysis is carried out to extract the multi-scale information by using Mallat decomposition and restructing algorithm, which has both row transformation and column transformation and decomposes approximate altitude field in every step. After n_w steps of the Mallat calculation, the altitude data is decomposed into four scales as roughness, waviness, form error and practical profile by the multi-scale exaction method. One case of the form error $h_p(x, y)$, extracted from original altitude information of fitting surface, is shown as Fig.2-a.

Because the main component of non-ideal geometric fitting surfaces in this paper is the form error, the surface geometric structural parameter of the separated surface altitude field of form error is evaluated, so the value of the equivalent flatness F_p is obtained. The cylindricity F_p^m of the practical spool valve is measured by special roundness measuring instrument. According to the value of F_p^m, calculate the altitude adjustment coefficient K of form error by Eq. (2), which expresses the ratio of form error of the measured surface to the simulated surface. Integrally scale the surface altitude field of form error $h_p(x, y)$ by the altitude adjustment coefficient K in the direction of z axis, so that the value of the adjusted equivalent flatness is the same as the cylindricity F_p^m of the practical spool valve. Fig.2-b shows the adjusted form error of the simulated surface.

$$K = \frac{F_p^m}{F_p} = \frac{F_p^m}{h_p(x, y)_{\max} - h_p(x, y)_{\min}} \tag{2}$$

The adjusted surface altitude field of form error is mapped to the smooth cylindrical surface which contains the dimensional discrepancy based on the hybrid dimensional modeling theory of part surface proposed by us in [13]. Each discrete point on the cylindrical surface needs to be deflected, where the deflection direction is the unit normal vector of each point on the cylindrical surface and the deflection distance is the altitude value of the point in the adjusted surface altitude field of form error. Then the non-ideal geometric surface model of precision couplings is established, which can describe the regular macro shape characteristic and its dimensional discrepancy of fitting surfaces of precision couplings and can also describe the irregular detailed form error of fitting surfaces very well. Fig. (3) shows a case of the non-ideal geometric surface model of precision couplings, which includes the dimensional discrepancy and the form error of the practical fitting surface.

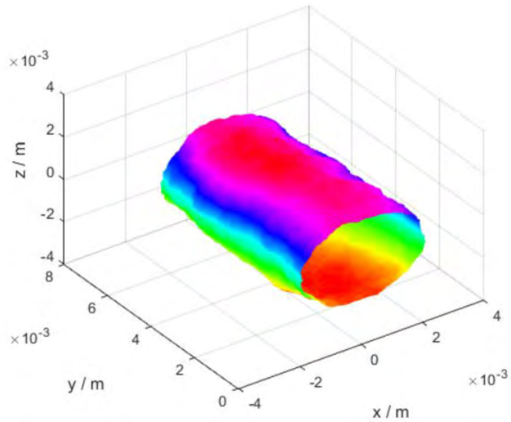


FIGURE 3. Non-ideal geometric surface model with both dimensional discrepancy and form error.

III. ANALYSIS OF FITTING PERFORMANCE OF PRECISION COUPLINGS BASED ON THE NON-IDEAL GEOMETRIC FITTING SURFACES

A. ANALYSIS OF FITTING PERFORMANCE OF PRECISION COUPLINGS ONLY CONSIDERING DIMENSIONAL DISCREPANCY

In this section, only the dimensional discrepancy of precision couplings is considered, while the fitting surfaces are supposed to be ideal smooth cylindrical surfaces, as shown in Fig. 4. The fitting accuracy of the spool valve is evaluated in this paper by the clearance sectional area instead of the clearance height, so that the influence of the position of the valve core in the valve sleeve on the fitting accuracy can be neglected. The effective clearance sectional area of a certain section of the spool valve can be calculated by the current dimensional discrepancies and by the radii of the inside and outside cylinder:

$$A_p = \pi (R + \delta_R)^2 - \pi (r + \delta_r)^2 \tag{3}$$

where δ_R and δ_r are dimensional discrepancies of the inside radius of the valve sleeve and the outside radius of the valve core respectively. For the spool valve, the nominal dimensions of the inside radius of the valve sleeve and the outside radius of the valve core should be equal [14], that is $R = r$. Then S in Eq. (4) is the theoretical clearance value of the spool valve only considering the dimensional discrepancy, and

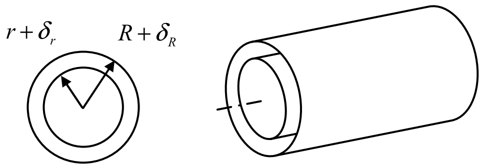


FIGURE 4. Fitting of valve core and valve sleeve only considering dimensional discrepancy.

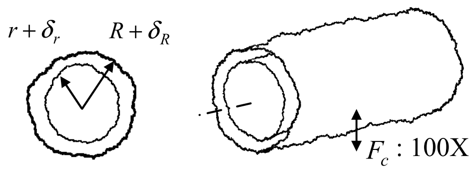


FIGURE 5. Fitting of valve core and valve sleeve considering both dimensional discrepancy and form error.

$\Delta R'$ in Eq. (5) is the dimensional discrepancy of the radius of the annular clearance.

$$S = \delta_R - \delta_r \tag{4}$$

$$\Delta R' = \frac{\delta_R + \delta_r}{2} \tag{5}$$

B. ANALYSIS OF FITTING PERFORMANCE OF PRECISION COUPLINGS CONSIDERING BOTH DIMENSIONAL DISCREPANCY AND FORM ERROR

In this section, both the dimensional discrepancy and the form error of precision couplings are considered. Because of the clearance fitting and relative motion of the spool valve during working process, the deformation of micro-bulges of the spool valve can be neglected. For the purpose of showing the fitting surfaces of the spool valve more clearly, the form error F_c in Fig. 5 is enlarged by 100 times in the radial direction. Adjust the position of the valve core and the valve sleeve in three-dimensional coordinates system, so that their axial cords coincide with the vector $n = (0, 1, 0)$. The fitting accuracy of the spool valve is also evaluated by the clearance sectional area, and the effective clearance sectional area of a certain section of the spool valve can be calculated by the contour lines of the current section. Then the clearance sectional area of the i-th section of the valve core and the valve sleeve is as follows:

$$A_i = \sum_j \begin{vmatrix} 0 & 0 & 1 \\ X_{sleeve\ i,j} & Z_{sleeve\ i,j} & 1 \\ X_{sleeve\ i,j+1} & Z_{sleeve\ i,j+1} & 1 \end{vmatrix} - \sum_j \begin{vmatrix} 0 & 0 & 1 \\ X_{core\ i,j} & Z_{core\ i,j} & 1 \\ X_{core\ i,j+1} & Z_{core\ i,j+1} & 1 \end{vmatrix} \tag{6}$$

where $X_{core\ i,j}$ and $X_{sleeve\ i,j}$ denote the x axis coordinate value of the i-th section$j$-th point of the fitting surfaces of the valve core and the valve sleeve respectively; $Z_{core\ i,j}$ and $Z_{sleeve\ i,j}$ denote the z axis coordinate value of the i-th section$j$-th point of the fitting surfaces of the valve core and the valve sleeve respectively. Calculate every section of precision coupling, and the effective clearance sectional area with current dimensional discrepancy and form error is obtained. Eqs. (7) and (8) are expressions of average clearance sectional area and minimum clearance sectional area, which can be used to characterize the fitting performance of precision couplings.

$$\overline{A}_p = \frac{1}{m}\sum_{i=1}^{m} A_i \tag{7}$$

$$A_{p\min} = \min (A_i) \tag{8}$$

When the dimensional discrepancy and the form error of precision couplings fluctuate in a certain range, the influence of non-ideal geometric fitting surfaces on the fitting performance of precision couplings can be investigated.

IV. PREDICTION OF LEAKAGE FLOW RATE BASED ON NON-IDEAL GEOMETRIC MODEL

A. CONSTRUCTION AND ANALYSIS OF NON-IDEAL GEOMETRIC THEORETICAL MODEL OF FLUID LEAKAGE

According to the classical theoretical formulae of the annular clearance flow, the leakage flow rate caused by the differential pressure between the valve core and the valve sleeve (differential pressure flow / Poiseuille flow) can be calculated as follows [15]:

$$q_1 = \frac{\pi d S^3}{12\mu l}\Delta p \tag{9}$$

where d is the diameter of the annular clearance; S is the effective clearance value; μ is the fluid dynamic viscosity; l is the length of the annular clearance; Δp is the differential pressure of the two ends of the clearance.

Moreover, the position of the valve core will be changed during working process, and the leakage flow rate caused by relative motion of the spool valve (shear flow / Couette flow) can be calculated as follows:

$$q_2 = \pm \pi d U \frac{S}{2} \tag{10}$$

where U is the relative velocity of the valve core and the valve sleeve; d is the diameter of the annular clearance; S is the effective clearance value.

When the direction of relative motion of the valve core to the valve sleeve is consistent with the direction of leakage flow, "$\pm$" in Eq. (10) is taken as "$+$", otherwise taken as "$-$". Therefore, the total leakage flow rate of precision couplings caused by the radial clearance (Couette-Poiseuille flow) is:

$$Q = q_1 + q_2 = \pi d \left(\frac{S^3}{12\mu l}\Delta p \pm U\frac{S}{2} \right) \tag{11}$$

Develop the classical theory of the annular clearance flow by introducing the dimensional discrepancy, the form error, the fitting accuracy and other parameters into the theoretical formulae, and the leakage flow rate can be calculated by non-ideal geometric factors. In this section, minimum clearance sectional area is used as the parameter of the fitting accuracy to calculate the leakage flow rate. Substituting $d = R + r + 2\Delta R'$ and $S = \frac{A_p}{\pi(R+r+2\Delta R')}$ into Eqs. (9) ~ (11), the non-ideal geometry based calculation formulae of the differential pressure flow, the shear flow and the total leakage flow rate are derived as Eqs. (12)~(14):

$$q_1 = \frac{A_p^3 \Delta p}{12\pi^2 \mu l \left(R + r + 2\Delta R'\right)^2} \quad (12)$$

$$q_2 = \pm \frac{U A_p}{2} \quad (13)$$

$$Q = \frac{A_p^3 \Delta p}{12\pi^2 \mu l \left(R + r + 2\Delta R'\right)^2} \pm \frac{U A_p}{2} \quad (14)$$

Considering the eccentricity of the valve core in the valve sleeve, the leakage flow rate caused by the differential pressure is larger than that of concentricity. So, Eq. (12) needs to be adjusted, and the adjustment coefficient is:

$$\eta = 1 + 1.5\varepsilon^2 \quad (15)$$

where ε is the eccentricity ratio of the valve core in the valve sleeve, $\varepsilon = e/S$, and e is the practical eccentric amount whose value range is $0 \le e \le S$. For the electro-hydraulic servo valve, the nominal dimensions of the inside radius of the valve sleeve and the outside radius of the valve core is equal, that is $R = r$, so considering the eccentricity of the valve core in the valve sleeve, the leakage flow rate caused by the differential pressure is:

$$q_1 = \frac{A_p^3 \Delta p \left[1 + 1.5\left(\frac{e}{\delta_R - \delta_r}\right)^2\right]}{48\pi^2 \mu l \left(R + \frac{\delta_R + \delta_r}{2}\right)^2} \quad (16)$$

In the working process of the electro-hydraulic servo valve, the fluid dynamic viscosity is influenced by the change of the fluid temperature, and Eq. (17) can be used to approximately calculate the fluid dynamic viscosity when the fluid temperature is t [16].

$$\mu = \mu_0 e^{-\lambda(t - t_0)} \quad (17)$$

where μ_0 is the fluid dynamic viscosity of the temperature t_0; λ is the fluid viscosity-temperature coefficient. Substituting Eq. (17) into Eq. (14), the non-ideal geometric factors-based calculation formula of the total leakage flow rate is derived as Eq. (18), which considers the eccentricity and the temperature change.

$$Q = \frac{A_p^3 \Delta p \left[1 + 1.5\left(\frac{e}{\delta_R - \delta_r}\right)^2\right]}{48\pi^2 l \mu_0 e^{-\lambda(t - t_0)} \left(R + \frac{\delta_R + \delta_r}{2}\right)^2} \pm \frac{U A_p}{2} \quad (18)$$

For a certain electro-hydraulic servo valve, its design radius and length can be considered as constant, and the influence of the dimensional discrepancy, the form error and the fitting performance on the leakage flow rate can be analyzed by the calculation formula in conditions of different eccentricity ratios, fluid dynamic viscosities, differential pressures and relative velocities.

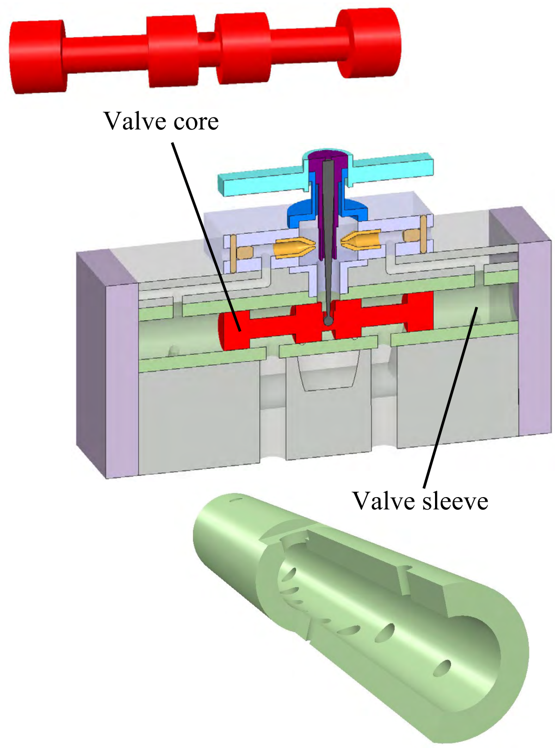


FIGURE 6. Ideal digital prototype of electro-hydraulic servo valve.

TABLE 1. The simulation parameters of surface model of spool valve.

D_i	G_i/M	φ_i
[2.31 2.38 2.80]	[3.36 3.36 1.36]×10^{-11}	[0.32π 1.85π 1.54π]

i_{max}	γ	M	n	L_1/m	L_2/m	n_w
3	1.5	10	14	0.06	0.2	3

B. VERIFICATION OF NON-IDEAL GEOMETRIC FLUID LEAKAGE BY cfd APPROACH

In this section, Gambit is used as the CFD pre-processing tool, and the non-ideal geometric model of the flow channel including the dimensional discrepancy and the form error of precision couplings is imported. For the flow type of this model is three-dimensional flow, the flow channel model can be meshed as tetrahedron, hexahedron, pyramid or wedge unit. Due to the small fitting clearance, the mesh of thin wall edge of the flow channel should be refined. The continuum type of the whole flow channel model is specified as fluid, while the boundary type of the front-end face is specified as pressure outlet, the back-end face is pressure inlet, and the inner and outer surface are walls. Then save the project as msh file and export it to Fluent.

For the CFD computational condition, the fluid is supposed to be incompressible Newtonian fluid whose density is $860 kg/m^3$, and the fluid dynamic viscosity is determined by the variable fluid temperature. Due to the small fitting clearance and the slow flow velocity, the Reynolds number is much less than 1000, so the flow condition in the flow

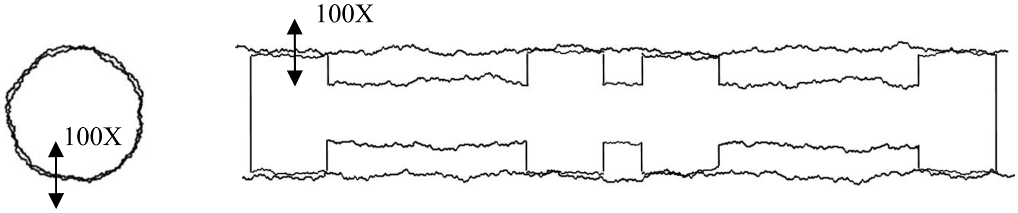


FIGURE 7. Sectional view of fitting surfaces of valve core and valve sleeve.

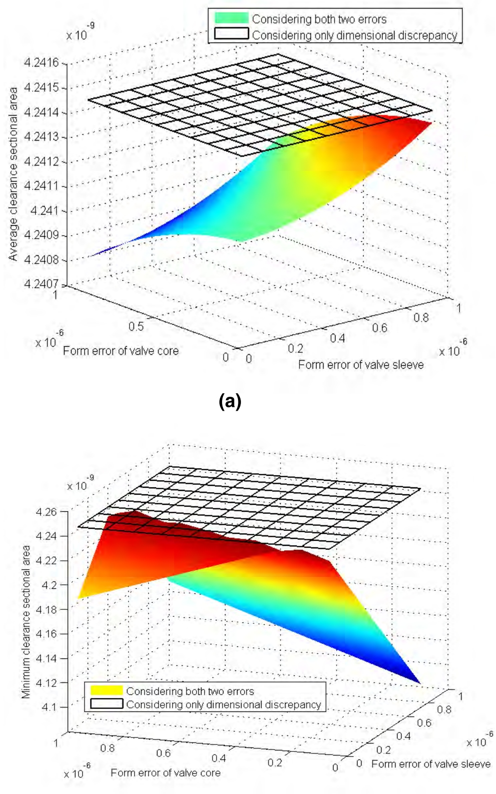
channel of precision couplings is defined as laminar flow and single-phase flow. The inlet and outlet pressure of precision couplings, the motion velocity and the motion direction of the fitting surfaces are defined respectively in Fluent. Therefore, the influence of different fluid dynamic viscosities, differential pressures and relative velocities on the leakage flow rate can be analyzed based on the non-ideal geometric model with the dimensional discrepancy and the form error.

V. EXPERIMENTAL RESULTS

The case of the fitting performance and the leakage characteristic prediction in this paper is the spool valve of the twin flapper-nozzle electro-hydraulic servo valve, as shown in Fig. 6. The fitting surface model of the spool valve including the dimensional discrepancy and the form error is established. The nominal dimensions of inside radius of the valve sleeve and outside radius of the valve core are both 2.25mm, and the influence of the part surface topography on the fitting accuracy and the leakage flow rate is analyzed based on the non-ideal geometric factors.

A series of non-ideal geometry-based models of fitting surface of spool valve is established using MATLAB R2012. The fractal parameters used to simulate these fitting surfaces are listed in Table 1. The sectional view of one case is shown in Fig. 7. In order to show the fitting surfaces of the spool valve more clearly, the surface topography in Fig. 7 is enlarged by 100 times in the radial direction.

The influence of the dimensional discrepancy and the form error on the fitting accuracy is analyzed by the method mentioned in section III B. When the dimensional discrepancies of the valve core and the valve sleeve are $1\mu m$ and $2\mu m$, and their form errors changed from $0.1\mu m$ to $1\mu m$, the influence of the form error on the fitting accuracy of the spool valve is shown in Fig. 8. The evaluating parameter in Fig. 8-a is average clearance sectional area, and the evaluating parameter in Fig. 8-b is minimum clearance sectional area. The grid in Fig. 8 represents the theoretical clearance sectional area calculated by Eq. (3) only considering the dimensional discrepancy. It can be seen from Fig. 8 that the clearance sectional area considering the form error is smaller than the theoretical clearance sectional area. Therefore, on the premise of satisfying the fitting accuracy, the values of form error of the valve core and the valve sleeve should avoid being chosen on the polygonal line in Fig. 8-b.

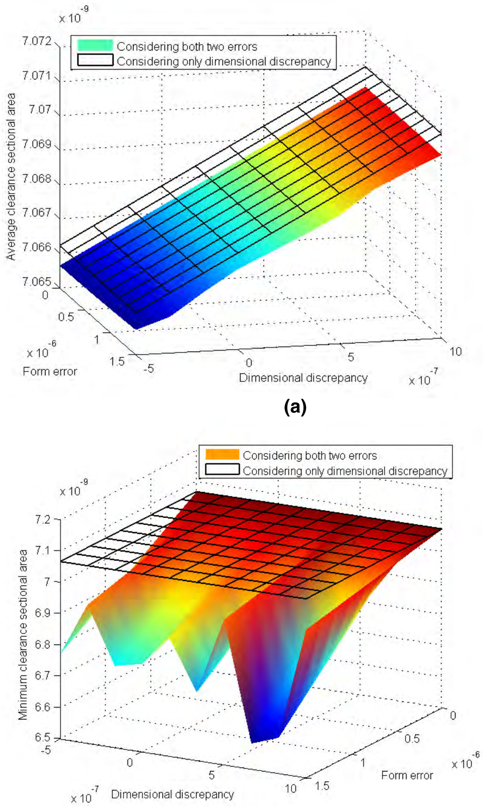


(a)

(b)

FIGURE 8. Influence of form error of valve core and valve sleeve on fitting accuracy of spool valve. (a) Average clearance sectional area. (b) Minimum clearance sectional area.

The form error and the dimensional discrepancy of the valve core are supposed to be the same as the valve sleeve, when the dimensional discrepancies of the valve core and the valve sleeve changed from $-0.5\mu m$ and $1\mu m$, and their form errors changed from $0\mu m$ to $1.5\mu m$, the influence of the form error and the dimensional discrepancy on the fitting accuracy of the spool valve is analyzed. The calculation result is shown in Fig. 9, where the evaluating parameter in Fig. 9-a is average clearance sectional area, and the evaluating parameter in Fig. 9-b is minimum clearance sectional area. The grid in Fig. 9 also represents the theoretical clearance sectional area calculated by Eq. (3) only considering the dimensional discrepancy. It can be seen from Fig. 9 that the dimensional discrepancy has the main influence on the fitting accuracy,



(a)

(b)

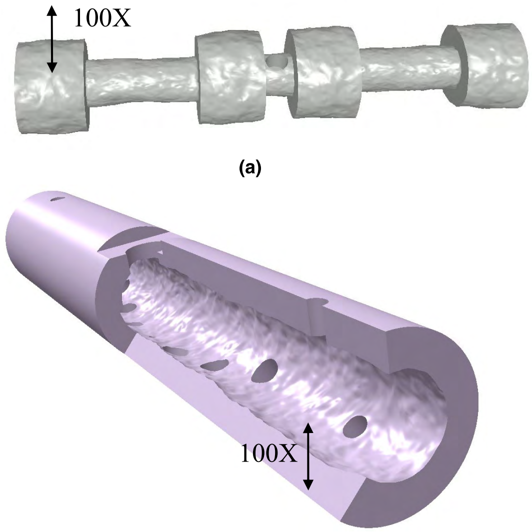
FIGURE 9. Influence of form error and dimensional discrepancy of valve core and valve sleeve on fitting accuracy of spool valve. (a) Average clearance sectional area. (b) Minimum clearance sectional area.

TABLE 2. Non-ideal geometric parameters of two spool valves.

	VALVE CORE		Valve sleeve	
	DIMENSIONAL DISCREPANCY	FORM ERROR	Dimensional discrepancy	Form error
Valve 1	$-1\mu m$	$0.001mm$	$2\mu m$	$0.001mm$
Valve 2	$-0.5\mu m$	$0.0008mm$	$1.5\mu m$	$0.0008mm$

while the change of form error has a certain fluctuant effect on average clearance sectional area, and the large form error has a violent concussive effect on minimum clearance sectional area.

Select two groups of spool valve from several machined valve cores and valve sleeves and measure their dimensional discrepancies and form errors (cylindricities). The measurement results are listed in Table 2. According to these parameters, the non-ideal geometric fitting surfaces of the valve core and the valve sleeve are generated and exported to CATIA V5-6R2017 to establish the CAD solid models of two spool valves. The non-ideal geometric solid part models of valve 1 are respectively shown in Fig. 10-a and Fig. 10-b, whose geometric errors are enlarged by 100 times in the radial direction to show the non-ideal geometric detail characteristics of the spool valve more clearly. Fig. 11 shows assembly simulation of the non-ideal geometric model of spool valve from different viewpoints. Then the solid model of the flow channel is established by three-dimensional Boolean operation on the non-ideal geometric model of valve 1, as shown in Fig. 12.



(a)

(b)

FIGURE 10. Non-ideal geometric solid part models of valve 1. (a) Solid model of valve core. (b) Solid model of valve sleeve.

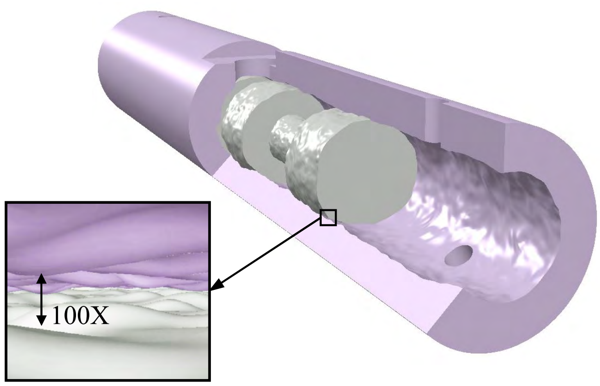


FIGURE 11. Assembly simulation of non-ideal geometric model of valve 1.

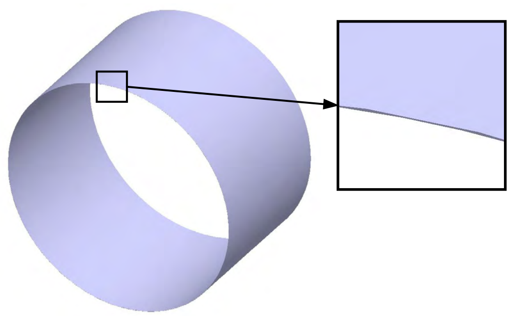


FIGURE 12. Non-ideal geometric solid model of flow channel of valve 1.

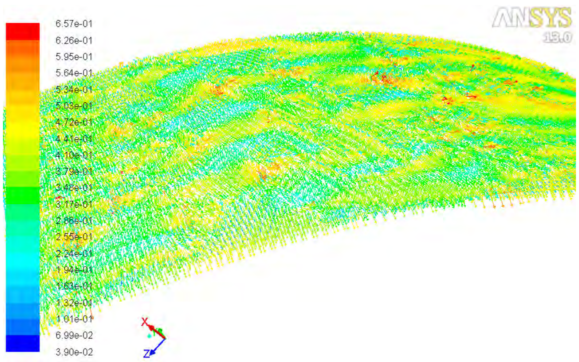


FIGURE 13. Velocity vector distribution of flow channel of valve 1

FIGURE 14. Experimental test bench of electro-hydraulic servo valve.

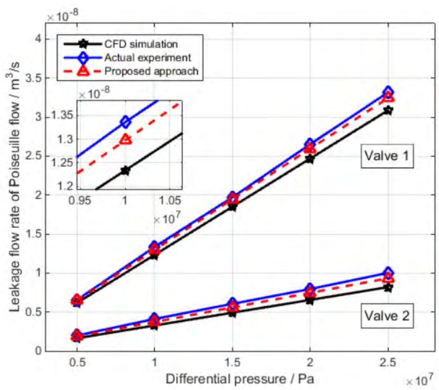


FIGURE 15. Curves of leakage flow rate of Poiseuille flow with change of differential pressure

The solid model of the flow channel is imported into Gambit 2.4.6 and meshed as 905736 tetrahedron units using TGrid type. Specify the pressure outlet, the pressure inlet, and the inner and outer wall of the flow channel and import the CFD pre-processing model into Fluent 13.0 to analyze the flow characteristic of the flow channel. The velocity vector distribution of the flow channel of valve 1 is shown in Fig. 13, when the pressure inlet is $20.6MPa$, the pressure outlet is $10.6MPa$, the fluid dynamic viscosity at $30°C$ is $0.0245\ N \cdot s/m^2$, and the relative velocity of the valve core

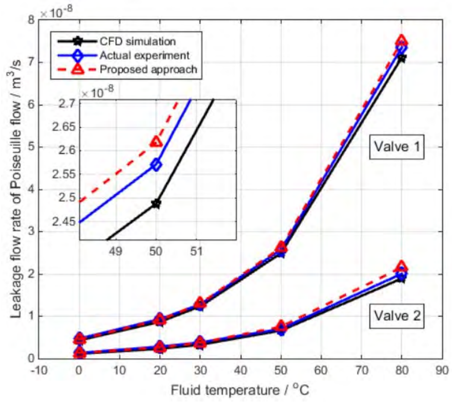


FIGURE 16. Curves of leakage flow rate of Poiseuille flow with change of fluid temperature.

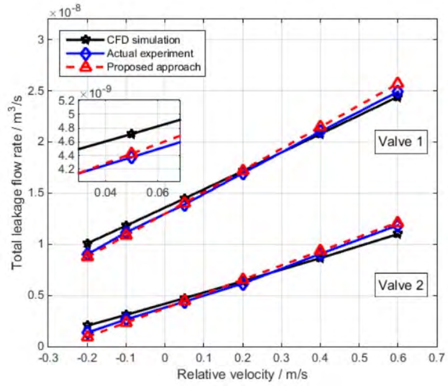


FIGURE 17. Curves of total leakage flow rate of Couette-Poiseuille flow with change of relative velocity.

and the valve sleeve is 0. Under this condition, the leakage flow rate of valve 1 is predicted as $1.234 \times 10^{-8} m^3/s$.

Then a series of simulation and actual experiments is carried out to analyze and verify the influence of various parameters on the leakage flow rate of the spool valve. The experimental test bench of electro-hydraulic servo valve is shown in Fig. 14, which can measure leakage characteristics of servo valve under different conditions. A comparison among simulation results, experimental results and prediction results by the proposed approach is made particularly as shown in Figs. 15∼17. Fig. 15 shows the curves of the leakage flow rate of the Poiseuille flow with the change of the differential pressure from $5MPa$ to $25MPa$, when the fluid dynamic viscosity at $30°C$ is $0.0245\ N \cdot s/m^2$, and the relative velocity of the valve core and the valve sleeve is 0. Fig. 16 shows the curves of the leakage flow rate of the Poiseuille flow with the change of the fluid temperature from $0°C$ to $80°C$, when the differential pressure is $10MPa$, and the relative velocity of the valve core and the valve sleeve is 0. The analysis results show that there is a rapid upward trend of the leakage flow rate with the rise of the fluid temperature. Fig. 17 shows the curves of the total leakage flow rate of the Couette-Poiseuille flow with the change of the relative velocity from $-0.2m/s$ to $0.6m/s$, when the eccentricity ratio of the valve core in the valve sleeve is $\varepsilon = 15\%$. The case study reveals that the mean error of the proposed approach is 3.46%, so it can be verified that the non-ideal geometry based prediction approach of the leakage characteristic of precision couplings has high credibility and feasibility. The prediction results provide credible reference for matching process planning of the spool valve.

VI. CONCLUSIONS

The non-ideal geometric model of precision couplings is established in this paper, which describes the regular shape characteristic of fitting surfaces in macro level, as well as characterizes the irregular detailed structures of fitting surfaces in micro level. The non-ideal surface model can reflect both the dimensional discrepancy and the form error of precision couplings and provide a geometric basis for the following performance prediction.

Moreover, the fitting performance of precision couplings is analyzed by calculating the clearance sectional area, and the leakage flow rate of the fitting clearance with comprehensive action of the dimensional discrepancy, the fitting accuracy, the relative velocity, the fluid temperature and the eccentricity ratio are predicted by proposed formulae. Finally, the efficiency and the feasibility of the prediction approach are validated by the CFD simulation and actual experiment.

In this paper, the prediction approach of the fitting performance and the leakage characteristic of precision couplings takes into account non-ideal geometry including the dimensional discrepancy and the form error of precision couplings. Further investigation may focus on the introduction of position error into non-ideal geometric model of precision couplings. For example, the axis of spool valve is not ideal straight line or the valve core is tilted in the valve sleeve.

REFERENCES

[1] B. Eryilmaz and B. H. Wilson, "Combining leakage and orifice flows in a hydraulic servovalve model," *J. Dyn. Syst., Meas., Control*, vol. 122, no. 3, pp. 576–579, 2000.

[2] D. Gordić, M. Babić, D. Milovanović, and S. Savić, "Spool valve leakage behaviour," *Arch. Civil Mech. Eng.*, vol. 11, no. 4, pp. 859–866, 2011.

[3] J. Ruan, R. Burton, and P. Ukrainetz, "An investigation into the characteristics of a two dimensional '2D' flow control valve," *ASME J. Dyn. Syst., Meas., Control*, vol. 124, no. 1, pp. 214–220, 2002.

[4] A. Y. Goharrizi and N. Sepehri, "A wavelet-based approach for external leakage detection and isolation from internal leakage in valve-controlled hydraulic actuators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4374–4384, Sep. 2011.

[5] A. Kovari, "Influence of cylinder leakage on dynamic behavior of electrohydraulic servo system," in *Proc. 7th Int. Symp. Intell. Syst. Inform.*, Subotica, Serbia, Sep. 2009, pp. 340–344.

[6] Z. Zhou, H. Peng, and S. Zeng, "Research on the influence factors of leakage in annular clearance seals," *Lubrication Eng.*, vol. 1, pp. 7–9, Jan. 2005.

[7] E. Strmčnik and F. Majdič, "Comparison of leakage level in water and oil hydraulics," *Adv. Mech. Eng.*, vol. 9, no. 11, pp. 1–12, 2017.

[8] X. Xue, "Analysis on the fluid-leakage characteristic in gaps of the hydraulic system," *Chin. J. Mech. Engineer*, vol. 40, no. 6, pp. 75–80, 2004.

[9] Y. Zhou and M. H. Hao, "The study of leakage of circular arc–involute–circular arc gear pump," *Adv. Mech. Eng.*, vol. 9, no. 9, pp. 1–9, 2017.

[10] H. Zhao and Y. Hou, "The application of micro cell analysis on formula deduction of the eccentric ring gap flow," *Chin. Hydraul. Pneum.*, vol. 11, pp. 49–52, Nov. 2005.

[11] K. Gui, *Fluid Mechanics*. Beijing, China: China Science, 2004.

[12] C. Qiu, Z. Liu, and J. Tan, "Multi-scale based unified modeling and simulation of part surface topography," *Int. J. Innovative Comput., Inf. Control*, vol. 8, pp. 1787–1798, Mar. 2012.

[13] C. Qiu, Z. Liu, and W. Bu, "Hybrid dimension based modeling of part surface topography and identification of its characteristic parameters," *Appl. Surf. Sci.*, vol. 258, no. 18, pp. 7082–7093, 2012.

[14] G. Ren, Z. Zhang, and Y. Zhou, *Manufacturing Process of Electrohydraulic Servo Valve*. Beijing, China: Astronautic, 1988.

[15] M. Lu and W. Li, *Fluid mechanics and hydraulic drive*. Shanghai, China: Tongji Univ. Press, 2006.

[16] X. Wang and H. Zhou, *Hydrodynamics and Hydraulic Transmission*. Beijing, China: Beihang Univ. Press, 2015.

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