Research on Clearance Flow of Microscopic Surface Influence

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Abstract

Using Weierstrass-Mandelbrot (W-M) function, characterization is done on the microscopic surface contours, structure function and scale consistent with a power-law relationship. The Weierstrass-Mandelbrot function is introduced to characterize the surface spool’s microscopic surface. It can be certified by the structure function and scale consistent with Power-Law. With CFD method, numerical simulation was made on the rough surface. The two-dimensional cross-section model of the valve-gap is established, and it is simulated by FLUENT and compared with the ideal smooth surface. Results show that rough valve clearance formed by the pressure drop is significantly larger than that of the desired glossy surface. In the end, this article shows that the roughness, good sealing and pressure maintaining requirement can be satisfied by increasing the annular groove.

Keywords: Fractal, Hydraulic Valve, Micro-flow Analysis, Surface Contour Fractal, Morphology

1. Introduction

The hydraulic valve is widely used in such industries as biological medicine, construction machinery and machine tools. Its market demand is expanding constantly, while its quality and techniques do not always live up to that demand.

One of the most serious problems is leakage, including two types: internal leakage and external leakage. The internal leakage is known as the oil flow in each of the cavities within the cavity, which is generally caused by a broken seal or a larger gap. This type of leakage will hamper the hydraulic system and even make the machinery unable to work properly. External leakage means the outflow of oil to the external environment, which damages the environment. The chief reason causing the leakage of a hydraulic valve is the relatively bigger gap in the cavity.

The relative roughness of microscopic surface will increase dramatically, as the gap scale becomes smaller, as in [1]. For small-scale passages (such as 200 μm ~ 3mm) and even micro-scale ones (such as 10μm ~ 200μm), in [2], the shape of the roughness surface and the relative roughness have an important impact on micro-flow.

Flow characteristics of throttle notches are important factors to optimum valves, and many methods have been employed to deeply study the fluid flow of different type valves. In [3] some methods were employed to analysis the flow of hydraulic components. The optimum design of a directional valve requires a preliminary estimation of the flow features. In order to solve this problem, many experimental measurements on the specific valve are needed. Alternatively, a numerical analysis can be performed by means of computational fluid dynamics (CFD) codes. CFD can help people understand the internal flow field and can provide the scientific means to describe the mechanism of fluid. The rapidly developing technique becomes more attractive as commercial computational fluid dynamics software becomes readily available, making structural optimization design of hydraulic components available based on flow field control. In [4] some characteristics were numerical analyzed using CFD methods, and numerical simulated results were reviewed to assess the utility of the new simulation for future studies and experiment design.

The computational fluid dynamics (CFD) has been showing a good prospect for the past decade. CFD is widely used for it can help people understand of cavitation from the Micro-level and it can provide the scientific means to describe the mechanism of fluid vibration[5]. The rapidly developing
technique becomes more attractive as commercial computational fluid dynamics software becomes readily available, making structural optimization design of hydraulic components available based on flow field control. In [6], the validity of a code implemented for modeling cavitation phenomena was checked by comparing data acquired by numerical simulations against data obtained for a simple contraction nozzle and for a real diesel injector nozzle. In China, many studies also have been conducted in this respect [7].

Gas-Relief Valve (GRV) [8] played a role of over-pressure protection to mechanical equipments and its faults will bring unpredictable severe accidents. So it is of important significance to diagnose the faults of GRV effectively. Small failure samples, as well as obtained leak magnitude without overall showing the actual leak situation of GRV, are two factors causing low diagnosis accuracy. A new approach is proposed for fault diagnosis of GRV in this paper. A novel pneumatic circuit acquiring leak upstream of input let of GRV is designed. Using support vector machines (SVM) based on binary tree structure to identify the failure pattern of GRV, is to solve the problem of artificial intelligence methods weak in small samples. The diagnosis results of experiments on 16 GRVs demonstrate the superiority of this approach. Besides leak through leakage hole of GRV, leak caused by deterioration of both fit clearance and mechanical sealing elements, is also acquired successfully. Compared with neural network, SVM achieves a higher diagnosis precision [9,10]. The influence of the leak on the diagnosis of different running statuses is also discussed.

The microscopic surface is a nonlinear and non-steady state of random process. In this paper, the fractal theory is used to analyze the characteristics of micro-flow. This paper is organized as follows. In section 2, the valve surface contour fractal phenomenon is confirmed to exit. In section 3, explains that the valve rough surface on the laminar flow played a certain antihypertensive role. In section 4, the valve spool with annular grooves can satisfy the roughness, good sealing and pressure-maintaining functions. Finally, our work of this paper is summarized in the last section.

2. Fractal Characteristics of Hydraulic Spool Surface

In European geometry of space, length, area and volume of an object were measured by unit of length, square and cube. In 1975, Mandelbort, as in [11], first proposed the idea "fractal", and revealed the relationship between fractal and physics, which is that complex irregular structure geometric dimension is not integer.

The hydraulic spool micro-surface shows statistical self-similarity and self-affinity, as in [12]. Accordingly, similar structure constantly appears on the surface at different degrees of magnification. That is, when the measurement scale is reduced, similar micro-structure can be seen, showing the presence of spool surface fractal.

2.1. Measurement Methods of fractal characterization

Weierstrass-Mandelbrot (W-M) function, such as in [13] was used to characterize the micro-rough surface with self-similarity and self-affinity. Expression for W-M function:

\[ Z(x) = G^{(D-1)} \sum_{n=m}^{\infty} \frac{\cos(2\pi\gamma^n x)}{\gamma^{(2-D)n}} \quad (1 < D < 2, \ \gamma > 1) \] (1)

Where \( Z(x) \) is the micro-surface height, \( x \) is displacement coordinates of the surface profile, \( D \) is the fractal dimension, \( G \) is the coefficient of the characteristic scale of the corresponding size of the \( Z(x) \), \( \gamma \) is the constant greater than 1, \( \gamma^n \) is spatial frequency of random surface profile, \( n_1 \) is minimum cut-off frequency used to describe structure and surface contour, \( \gamma^n = 1/L \), \( L \) is the measured sample length.

Structure function of the \( \text{Str}(\tau) \) formula of rough surface profile \( Z(x) \) is

\[ \text{Str}(\tau) = \langle (Z(x+\tau) - Z(x))^2 \rangle = C \tau^{2(2-D)} \] (2)
τ is the scale, D is the fractal dimension, C is the scale coefficients of fractional dimensionless number. Structure function and scale are well characterized by the power-law model, which also explained why microscopic surface of hydraulic valves have fractal characteristics.

2.2. Fractal Characteristics of Valve Spool Surface

Using surface profile-meter (CV-3000), on different scales, it can be seen that the morphology of the valve core surface contour have self-similarity and self-affinity. In Fig. 1, Fig.2 and Fig.3, Z (x) is the contour height, N is the collection of data points. With the increase of resolution, the contour surface of the valve repeatedly shows similar microscopic fine structure. So it can be confirmed that the surface contour fractal phenomenon does exist
3. Effect on the Micro Flow of the Spool Surface to Valve Clearance

Hydraulic valve is one of the basic precise elements, while valve spool surface roughness can not go beyond 0.3~0.5μm. Valve cavity surface roughness can meet the requirement of 0.6~0.8μm for general purposes, with valve clearance between 3~10μm. Seal performance of the hydraulic valve largely depends on the flow state and flow resistance of the fluid which runs through the valve cavity. The seal gap is very small (less than 10 μm), usually under laminar flow, as in [13]. Laminar flow in the gap of a valve can be described by the Reynolds equation. The small clearance flow is mostly one of viscous flow. Viscous flow is subject to fluid cohesion as well as fluid and solid surface, while in space micro-flow the effect of inertial force is secondary.

3.1. Valve Clearance Geometry Model

CFD method was adopted to simulate the influence relation between microscopic surface roughness and micro-flow in clearance in two-dimensional cross section form. Spool surface and valve cavity surface are considered as isotropic and finely machined surface, which surface morphology is characterized by fractal feature. According to the W-M fractal function (Equation 1) proposed by Weierstrass and Mandelbrot, cross-sectional clearance contour curve can be constructed as fractal dimension D.

As shown in Fig.4, the period of D=1.54 of cross section contour map was selected, where the length is 50μm, and the width of clearance is 6μm. The upper curve shows the valve cavity surface contour, and the lower is the valve spool surface contour.

3.2. Analysis Based on FLUENT Clearance Flow

The following assumptions are made first: 1) the physical volume does not change with the time, and the flow is in a steady state, 2) The fluid is a Newtonian fluid, and it follows the Newtonian viscous law, i.e., the shear stress is proportional to the shear strain rate, 3) the thermal effect on fluid is not taken into account, 4) the fluid in the valve cavity flow is laminar, and there is no vortices and turbulence, 5) the flow if incompressible.
In this paper, the fluid used is HM46 hydraulic oil. Hydraulic oil temperature is $T = 300K$, density is $860kg/m^3$, and kinematic viscosity is $44mm/s$. Boundary conditions: inlet pressure is $1MPa$, and outlet pressure is $0.1MPa$.

In order to display the valve clearance flow image, the surface characteristics between the ideal and non-ideal surface were analyzed. Velocity distribution of rough surface and smooth surface are shown in Fig. 5 and Fig.6, in which the maximum flow rate is $35.7m/s$ (Fig. 5), and the maximum flow rate is $45.9m/s$ (Fig. 6). Rough surface increases the bottom thickness of laminar flow. Thus, from a certain point of view, the hydraulic oil outlet area is reduced, which proves in part that the rough surface increases flow resistance.

Figure 4. $D=1.54$ Cross-section of the hydraulic valve-gap

Figure 5. Velocity magnitude contours of the valve gap with the rough surface

Figure 6. Velocity magnitude contours of the valve gap with the ideal smooth surface
Shown in Fig.7 and Fig.8, the inlet to outlet of pressure drop with rough the surface of valve spool was significantly greater than the ideal smooth surface valve spool. This explains that the rough surface on the laminar flow played a certain antihypertensive role. Negative pressure was formed in fluid outlet. According to Bernoulli principle, that is fluid dynamic pressure and static pressure is equal to the total pressure, and the total pressure is constant. When the fluid flow velocity increases, the dynamic pressure increases. To ensure balance of the total pressure, static pressure will reduce, which generates negative pressure.

Figure 7. Static pressure contours of the valve-gap with the rough surface

Figure 8. Static pressure contours of the valve-gap with the ideal smooth surface

Figure 9. Spool with the ring groove
4. Improvement on the Valve Spool

As has been discussed, microscopic surface roughness has an obvious effect on valve clearance flow. But in fluid machinery industry, degrees of roughness directly affect the valve assembly and seal, while better performance does not necessarily follow rougher surface. Processing annular groove in the valve spool can also exert a similar effect. Several annular grooves were processed in the shoulder in general, as shown in Fig.9, with width at 0.3–0.5mm, depth at 0.5–0.8mm, and spacing at 1–5mm. The annular groove depth is larger than the gap, and so there is almost similar pressure around the annular groove so that the unbalance force reduced greatly. Shown in Fig.10 and Fig.11, the outlet velocity with an annular groove is smaller than that without annular groove. Shown in Fig.12 and Fig.13, the pressure drop is higher than that in the ordinary spool without annular groove. Therefore, the valve spool with annular grooves can satisfy the roughness, good sealing, and pressure-maintaining functions.
5. Conclusions

Hydraulic valve surface displays statistical self-similarity and self-affinity. Using w-m function, characterization was done on the microscopic surface contours, structure function and scale consistent with a power-law relationship. All these show a very good fractal feature in hydraulic valve surface microstructure.

Using fractal characterization of curves, a micro valve gap of two-dimensional cross section model was established. With the CFD method, numerical simulation was made on the rough surfaces, and then a comparison was made between the simulated results and the ideal smooth surface. Results show that rough surface increases the bottom thickness on both sides in laminar flow, which is to reduce the oil outlet area in the hydraulic oil. From a certain point of view, the hydraulic oil outlet area is reduced, which proves in part that the rough surface increases flow resistance. Rough valve clearance formed by the pressure drop is significantly larger than that on the desired glossy surface.

Increasing the annular groove can satisfy among the roughness, good sealing and pressure-maintaining requirement.
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7. References