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Modelling of fluid continuum considering 3D surface parameters in hydraulic assemblies

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ABSTRACT

Friction in servo hydraulic assemblies reduces the response characteristics of the system. The friction is influenced by various factors including the geometry (form and surface errors) of the sliding surfaces. In this work, functionally significant 3D surface parameters from the Birmingham parameters are investigated for reduced friction. A 3D surface modelling approach is presented using random process modelling as the basis. An exponential decay areal autocorrelation function is used to model the grinding and honing processes which are commonly employed for the manufacture of the hydraulic assemblies. Honed surface is modelled with the crosshatches of appropriate angle. Method of surface modelling is validated using the data obtained through measurements on a practical surface. Different surface maps with varying surface parameters of the ground and honed surfaces are generated. The fluid continuum gap geometries of the hydraulic assemblies are modelled using these surface maps as envelopes. Pressure distribution, velocity and viscous friction force are used as measurands of the frictional characteristics. Using computational fluid dynamics (CFD) approach, these measurands are evaluated for different functionally significant Birmingham parameters. Based on further analysis, negative skewness, lower kurtosis values, higher valley fluid retention index were found to have lower frictional characteristics.

1. Introduction

Electro hydraulic servo systems (EHSS) have wide applications in power and motion transmission devices due to their high power density coupled with controllability. The performance of the EHSS (based on quickness of response, positioning accuracy, energy loss, etc.,) is affected by friction in the mating parts of the assemblies such as spool valves and actuator piston. This friction is a function of load, which acts on the assemblies, viscous drag of the fluid, gap geometry, form error and surface topography of the machined component.

To reduce the friction due to form and surface errors, precision components used in EHSS are given with stringent tolerances, hence difficult to manufacture and lead to higher production cost. Components cannot be machined to geometric perfection. They have form and surface errors that lead to varying gap geometry between the sliding parts in the hydraulic assembly and contribute to the friction. Few attempts were reported on the influence of form errors in hydraulic assemblies [1–4]; but no efforts have been made so far to study the influence of 3D surface topography parameters except R_a [1]. This work is an attempt to study the influence of functionally significant 3D surface topography parameters particularly for reduced friction in EHSS and other hydraulic assemblies such that its performance can be improved.

1.1. Lubrication between the sliding surfaces

In EHSS assemblies where the radial clearances commonly ranges from 5 to 10 μm and roughness value (R_a) of the order of 0.5–0.6 μm forming the lubrication film parameter greater than 5. Thus, hydrodynamic lubrication characteristics are the major contributing factor for friction reduction [5].

2. Need for 3D surface topography studies in hydraulic systems

Surface topography can contribute to good fluid retention property along with the chemical property and other physical metrology parameters like hardness, residual stress, etc., of the material [6]. Surface asperities or imperfections puncture the lubricant film, creating metal-to-metal contact; hence can act as a source of friction and wear. Despite the use of lubricant, a surface with good lubricant retention property must be implemented. Honing operation that

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Nomenclature

D	diameter of the piston/spool (m)
F_{fr}	viscous friction force (N)
R_a	centerline or arithmetic average (μm)
S_a	arithmetic mean deviation of the surface (μm)
S_{bi}	surface bearing index
S_{ci}	core fluid retention index
S_{ku}	kurtosis of surface height distribution
S_{pk}	reduced summit height in DIN 4776 parameter set (μm)
S_q	root mean square deviation of surface texture (μm)
S_{sk}	skewness of surface height distribution
S_t	maximum peak to valley height (μm)
S_{vi}	valley fluid retention index
S_{vk}	reduced valley depth in DIN 4776 parameter set (μm)
v_y	velocity of the fluid in axial (y) direction (m/s)
x	length of the piston/spool in circumferential (x) direction (m)
y_{max}	length of the piston/spool (m)
z	height of the surface data point (μm)
z_g	height of the gap geometry (m)

Greek letters

β_x	correlation length in circumferential (x) direction (μm)
β_y	correlation length in axial (y) direction (μm)
μ	coefficient of viscosity of the fluid (kg/m s)
τ	spacing value in AACF (μm)

generates crosshatches of deep valleys provides higher lubricant retention property of the surface. Hydraulic cylinders and spool sleeves widely employ this manufacturing process for lubricant retention. Piston or spool is normally finished by grinding process and in some cases, a coating follows. This imparts different surface topography that influences the lubrication characteristics. Hence in this work, three-dimensional surface topography of varying parameter values are modelled and frictional characteristics are evaluated.

The significance of micro-geometry on friction is widely reported in literature but they were based on various 2D surface parameters [1,7]. In 3D surface analysis, a few parameters were studied for asperity level contact analysis using finite element method (FEM) in non-Gaussian surfaces [8]. Ramesh et al. [9] have experimentally evaluated friction and correlated with 3D surface parameters such as S_q (rms deviation from mean plane), S_{ds} (density of summits) parameters. Further, Par Nyman et al. [10] have experimentally evaluated Birmingham parameters for clutch plate applications. But, all these micro-geometry studies [7,9,10] are essentially meant for materials with sliding friction and no lubricant present between them and do not address the hydraulic systems. Only R_a parameter is investigated for frictional response of the hydraulic systems [1]. But, surface topography is not consistent for the same R_a value. In other words, different surface profiles have different functional behaviour but can have the same R_a value. The profile traced in one direction gives some idea about the roughness of the surface but not the complete geometrical nature of the surface. Therefore, only surface characterisation based on 3D surface parameters can give the complete geometrical and reliable information about the surface. But, no work has been reported on the influence of three-dimensional surface parameters on hydraulic systems.

The functionally significant surface parameters from the 14 Birmingham parameters [11] were considered in the present study, which include S_{sk}, S_{ku} (height parameters) and S_{bi}, S_{ci} and S_{vi} (functional parameters).

3. Three-dimensional surface modelling

To evaluate the influence of different 3D surface parameters, surface maps with varying parameter values are essential. Considering the difficulty of manufacturing the part with desired surface topography variations, it is necessary to theoretically generate the surface with the desired 3D parameters. Some surface generation algorithms [8,12,15] were reported but they focus on few surface parameters than a specific machining process. In this work, a surface generation method that can generate grinding and honing process used in hydraulic assemblies is developed.

3.1. Surface generation

Grinding and honing are basically random abrasive processes. Hence, random process modelling is assumed as the basis [12–14] for surface generation. First step in surface generation is to generate non-Gaussian random numbers of the required distribution (with specific skewness and kurtosis values). Second step is to impart specific decay trend and dependency between the consecutive data points without loosing the amplitude distribution of the data. Detailed procedure of the surface generation procedure is presented (Fig. 1).

Random numbers of uniform distribution is generated. The required probability density function (PDF) profile is drawn (Fig. 2) and polynomial function is fitted using the coordinates of this PDF profile. This PDF function is plotted in the range of the generated random uniform distribution and it is used as filter to obtain non-Gaussian surface by accepting the data points that lie below this curve and rejecting the data points that lie above the curve (Fig. 2).

The generated non-Gaussian data set $g(z)$ is based on amplitude distribution function only (or PDF) and does not contain any spatial dependency between the consecutive data points. But, machined surfaces have a particular decay trend between them according to the machining process [6]. Literature reveals that most of the machined surfaces have decay trend of exponential or exponential plus cosine function [6,11]. Since grinding and honing are random abrasive processes whose surface follows exponential decay areal autocorrelation function (AACF) [15], AACF of exponential decay trend is considered in this work and is given by

$$\mathrm{AACF}(\tau_x, \tau_y) = S_q^2 \exp\left\{-2.3\left[\left(\frac{\tau_x}{\beta_x}\right)^2 + \left(\frac{\tau_y}{\beta_y}\right)^2\right]^{1/2}\right\} \quad (1)$$

In this work, an isotropic surface is considered for which $\beta_x = \beta_y = \beta$. However, this method can support anisotropic surfaces also.

If generated non-Gaussian data set $g(z)$ is multiplied with assumed areal autocorrelation function in frequency domain, the resulting multiplicand in spatial domain (Fig. 1) will have the corresponding decay trend of the AACF and the amplitude distribution given by the filter function. To summarize the procedure:

Transformed non-Gaussian data set in frequency domain is given as

$$G(\omega_z) = fft(g(z)) \quad (2)$$