THE EFFECT OF 3D ANISOTROPIC ROUGH SURFACE ON FRICTION IN PRECISION HYDRAULIC ASSEMBLIES

Manesh K. Kailathuvalappil\textsuperscript{1}, Ramamoorthy B.\textsuperscript{1}, Singaperumal M.\textsuperscript{2}

\textsuperscript{1}Manufacturing Engineering Section
Department of Mechanical Engineering
Indian Institute of Technology Madras, Chennai, Tamilnadu, India

\textsuperscript{2}Precision Engineering and Instrumentation Lab
Department of Mechanical Engineering
Indian Institute of Technology Madras, Chennai, Tamilnadu, India

1. INTRODUCTION

The functional performance of precision hydraulic assemblies is closely linked to the geometric properties of the surfaces of its components. At stringent tolerance levels, surface topography (the characteristic of the manufacturing process used to generate the same) can contribute to good fluid retention property to the components. Hence, the prediction of functional behaviour of precision hydraulic assemblies requires consideration of 3D surface roughness of its mating components.

Significance of micro geometry on friction is widely reported in literature but they were based on various 2D surface parameters. 3D surface analysis is also reported in the area of asperity level contact analysis. All these micro geometry studies are essentially meant for materials with sliding friction and do not address hydraulic systems.

Prediction of the functional behaviour of these assemblies requires input of 3D surface data, which could be obtained from profilometer. But measured profiles cannot be used to determine an optimized surface roughness, in terms of 3D surface roughness parameters, for a specified application. Therefore, a simulation procedure for the generation of arbitrarily defined rough surfaces is needed. A surface profile, being of random type, can be defined (in a statistical sense) by two characteristics: the height distribution and the autocorrelation function (ACF) \cite{1}. Hence, random process description of engineering surfaces makes it possible to generate a rough surface by numerical simulation.

In this paper, a procedure is developed for computer simulation of 3D non-Gaussian anisotropic rough surfaces with specified anisotropy, standard deviation, skewness and kurtosis and to model 3D fluid continuum representing the fluid flowing through the clearance gap between the mating components of the precision assemblies. The procedure is then implemented to study the effect of 3D anisotropic rough surface on friction in spool-sleeve assembly of servo valve.

2. GENERATION OF ROUGH SURFACE

In this section, a computer program is developed based on 2D digital filter technique \cite{2} for modeling 3D rough surfaces. Initially, random non-Gaussian surface data is generated with different histogram inputs to obtain specified skewness and kurtosis. Further, areal autocorrelation function (AACF) is used for establishing dependency between the consecutive data points such that the generated surface is in conformance with the machining process considered.

For a Gaussian rough surface with prescribed autocorrelation function, two surface roughness parameters are used to represent its characteristics: the standard deviation of surface heights ($\sigma$), and the correlation length ($\tau$). Areal autocorrelation function for ground surfaces can be approximated as an ellipsoidal, which is expressed as:

\[ R(\tau_x, \tau_y) = \sigma^2 \exp \left\{ -\left[ \frac{\tau_x}{\tau_x^*} \right]^2 + \left[ \frac{\tau_y}{\tau_y^*} \right]^2 \right\} \]

(1)

Where, $\tau_x, \tau_y$ are the correlation distances in x and y directions, $\tau_x^*, \tau_y^*$ are the correlation lengths of the surface profiles in x and y directions at which the ACF in the direction of the profile decays to a threshold $r$.

The method to generate three-dimensional surfaces can be summarized as follows:

Suppose $\eta(i,j)$ is a sequence of random number having a Gaussian distribution of known
standard deviation \( \sigma \), the simulated rough heights \( z(i, j) \) can be taken as:

\[
z(i, j) = \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} h(k, l) \eta(i + k, j + l) \tag{2}\]

Where \( h(k, l) \) is filter function which defines the system. By signal process theory, \( z(i, j) \) will possess the same height distribution with the input sequence \( \eta(i, j) \). The Fourier transform of Equation (2) is given as:

\[
Z(\omega_x, \omega_y) = H(\omega_x, \omega_y)A(\omega_x, \omega_y) \tag{3}\]

Where \( A \) and \( Z \) are Fourier transform of \( \eta \) and \( z \) respectively, and \( H \) is the transfer function of the system, which can be calculated, for a linear system, as:

\[
S_z(\omega_x, \omega_y) = |H(\omega_x, \omega_y)|^2 S_\eta(\omega_x, \omega_y) \tag{4}\]

Where \( S_\eta \) is the spectral density of input sequence \( \eta(i, j) \), which gives a constant value for a random sequence in white noise type; \( S_z \) is the spectral density of output sequence \( z(i, j) \), i.e. the Fourier transform of the expected autocorrelation function \( R(\tau_x, \tau_y) \). Thus, the filter coefficient \( h(i, j) \) can be obtained by applying inverse Fourier transform to \( H(i, j) \).

When non-Gaussian rough surface is expected, the Gaussian input sequence \( \eta(i, j) \) should be first transformed to another sequence \( \eta'(i, j) \) with appropriate standard deviation \( \sigma \), skewness \( S'_{sk} \) and kurtosis \( S'_{ku} \) using Johnson translator system of frequency curves [3], then let this new sequence pass through the filter to obtain the output sequence \( z(i, j) \), which possesses the specified standard deviation, autocorrelation function, skewness and kurtosis. The skewness \( S'_{sk} \) and kurtosis \( S'_{ku} \) for the modified input sequence \( \eta'(i, j) \) can be obtained by the following relation:

\[
S'_{sk} = S''_{sk} \sum_{i=1}^{n} \theta_i^2 \left( \sum_{i=1}^{n} \theta_i^2 \right)^{-3/2} \tag{5}\]

\[
S'_{ku} = [S'_{ku} + 6 \sum_{i=1}^{n} \sum_{j=1}^{m} \theta_i^2 \theta_j^2] \left( \sum_{i=1}^{n} \theta_i^2 \right)^2 \tag{6}\]

A typical anisotropic rough surface, generated with \( \tau_x = 60, \tau_y = 5 \), \( S_{sk} = -0.7 \) & \( S_{ku} = 4.0 \), and its areal autocorrelation function (AACF) are presented in Figure 1. In this study, nine ground surfaces with \( \sigma = 0.4 \), Kurtosis=4.0 and varying skewness and correlation distances \( \tau^x, \tau^y \) and a similar set of another nine rough surfaces with \( \sigma = 0.2 \) are generated. The parameters are made in conformance with the spool valve surface. One honed surface is generated, representing the sleeve, by post processing the simulated ground
surface with $\sigma = 0.3$ for generating cross hatches of 55° hone angle. Only spool surface topography is varied in this study.

3. MODELING AND SIMULATION

Three-dimensional CAD surface models were generated using Non Uniform Rational B-Spline (NURBS) interpolation from the generated surface maps. 3D Fluid continuums, of thickness equal to the radial clearance of the assemblies, were then modeled with the generated sleeve and spool rough surface models as envelopes. A radial clearance of 4 $\mu$m is used. Surfaces were assumed to be ergodic. Hence fluid continuum of 400x400 $\mu$m$^2$ size only was considered, in accordance with the computation power of the computer, from a section at the centre region of the EHSS assembly. MIL-H-5606 E fluid was considered as the medium. Three dimensional, steady, laminar flow was assumed. The gap geometry is evaluated with known pressures as boundary conditions. Pressure inlet and pressure outlet for the modeled fluid continuum were calculated as 2.81 MPa and 2.60 MPa respectively by conducting similar test, but on the macro geometry of the assembly with inlet pressure of 5 MPa and outlet pressure of 0.1 MPa for the assembly. The spool surface was assumed to be moving with a uniform velocity of 1m/s and the sleeve at rest. The modeled fluid continuum was discretised and analysed by Computational Fluid Dynamics (CFD) technique, using the commercially available CFD software, Fluent. After solving, pressure and velocity data were extracted from the grid. The viscous friction force exerted on the piston/spool in the direction of gap length is,

$$F_v = \int_0^{\pi d} \int_0^{y_{max}} \mu \frac{dv_y}{dz} dx dy$$

Where, $\mu$ is the coefficient of friction.

Viscous friction force of all the gap geometries were evaluated and compared.

4. RESULTS AND DISCUSSION

The pressure data of the grid in the flow direction was considered for analysis. Only a small deviation in pressure distribution was observed (of the order few kPa) between the evaluated surfaces (gap geometries). However this is significant in the first stage of EHSS assemblies. As the pressure and velocity profiles exhibits highly irregular variations with surface topography due to the irregular converging and diverging flow paths caused by the topography of surfaces, for comparison purpose, isotropic surface with $x = 60$, $y = 5$ was chosen as reference to evaluate the deviation of these parameters for different surface topographies.

The variation of Mean pressure deviation as a function of skewness is presented in figure 2. The Figure shows that pressure build up in the radial clearance is more with negatively skewed surface than with a positively skewed surface. This may be because negatively skewed surfaces exhibit more material in peak zone and they have shallow valleys that can retain fluid. Hence the fluid that enters the valley is pushed against the opposite wall, which creates flow.

**FIGURE 2. Variation of Mean Pressure Deviation as a Function of Skewness, (a) at Two Different Anisotropic Conditions (b) at Two ‘$\sigma$‘ Values.**
Resistance and hence the pressure increase. Figure 2(a) reveals that anisotropy of the surface supports this phenomena of pressure build. When the flow takes place in a direction inclined to the direction of lay, resistance to flow of fluid will be more, that also aids the pressure build up. But as skewness increases, pressure build up is getting reduced. This may be because, in the present analysis, Kurtosis kept constant. When pressure increase, velocity of flow will decrease, hence the viscous friction force also decreases and this is well supported in figure 3. Standard deviation of surface irregularities also supports pressure build, as shown in the figure 2(b) and figure 4; but its effect is very minimal.

5. CONCLUSION

In this research work, a simulation procedure is developed to study the effect of 3D anisotropic surface roughness on friction in precision hydraulic assemblies. It is found that anisotropy of the surfaces aids the assembly to develop pressure within the radial clearance. The results indicate that for better functional performance, surfaces of the assemblies need not be too smooth. Further studies have to be carried out, to determine an optimized surface roughness from the view point of functional behaviour.

6. REFERENCE