Research on Mechanism of Film Pressure Loss in Water-lubricated Bearing

WANG Lun¹,², WANG Nan¹,²*, DU Yubo³, YANG Litao¹,², WANG Peng¹,², YUE Xiaokui³

¹School of Mechanical Engineering, Shaanxi University of Technology, Hanzhong 723000, China
²Shaanxi Key Laboratory of Industrial Automation, Hanzhong 723000, China
³National Key Laboratory of Aerospace Flight Dynamics, Northwestern Poly technical University, Xi’an 710072, China
Email: 1747776792@qq.com

Abstract. Due to the low viscosity of water, the water film is not easy to form, and the water-lubricated bearing system has the characteristics of airtightness. Therefore, it is difficult to obtain an accurate water film pressure distribution through experiments. Aiming at the loss of water film pressure in the process of water film pressure transmission caused by L-type pipeline in the existing wireless sensor testing methods for water film pressure, a mathematical model of water-lubricated bearing system pipeline pressure loss is established by numerical analysis method, and the corresponding physical model is established by using ANSYS software. The mechanism of pressure loss is studied by simulation. Finally, the test results were corrected and analyzed. The results show that the higher the flow rate of lubricating water at the inlet of the pipeline, the greater the pressure loss of the water film; the higher the shaft speed, the greater the local pressure loss; the longer the pipeline, the greater the pressure loss of the straight pipe section of the L-shaped pipeline, and the dynamic condition of the pipeline The pressure loss and energy loss are much more severe than static conditions.

1. Introduction
The water film pressure is the basic parameter of the water-lubricated bearing. The important characteristics of the bearing, such as the thickness of the water film, the lubrication state of the bearing, can be obtained through the in-depth study on the water-film pressure of the bearing. However, the water film pressure is not easy to obtain and the lubrication state of the bearing is more complex. The related research of water film pressure is usually based on numerical calculation or software simulation. Because mathematical and physical approximations are performed in the
calculation\textsuperscript{[1\textasciitilde3]} or simulation\textsuperscript{[4\textasciitilde6]}. Through the continuous efforts of researchers, several water film pressure test methods\textsuperscript{[7]} have been put forward, but there are still different degrees of problems, the water film pressure at the limited point can only be measured, and the continuous pressure distribution of the radial section of the bearing cannot be obtained. In order to solve the above problems, after long-term research by our team, a non-invasive water lubrication bearing water film pressure is proposed, that is line sensing pressure test method. With the deepening of the research, it is gradually found that the proposed wireless sensing method of water film pressure, due to the installation of L-shaped diversion hole on the rotating shaft, will lead to pressure loss in the transmission process of water film pressure, which will affect the test accuracy. Therefore, based on the actual working conditions, the mathematical model of pressure loss of water lubrication system pipeline is established in this paper, and the shaft model and the physical model of pipeline are established by using ANSYS software. The influence of performance parameters on water film pressure of water-lubricated bearing under different working conditions is analyzed, and the basic law of pressure loss is obtained. Finally, the water film pressure test data of water-lubricated rubber bearings are corrected by using the research results, and the results are compared with the simulation results.

2. Problem Description
The water film pressure test bench is shown in reference\textsuperscript{[8]}. Fig. 1 is the schematic diagram of the axial structure of the rotating shaft. Six radial draft holes are evenly spaced along the axis (R1\textasciitilde R6 is the water film pressure measurement point). At the right end of the shaft, there are six axial draft holes connected to the radial pilot holes (A1\textasciitilde A6 is the installation point of the sensor), and there are six axial pilot holes at the right end of the shaft (A1\textasciitilde A6 is the installation point of the sensor). The axial diversion hole is uniformly distributed in the circumferential direction and runs through the radial diversion hole. The water film pressure is transferred to the right sensor through the diversion hole for further testing.

As can be seen from figure 1, due to the existence of L-shaped pipeline, the water film pressure will inevitably be affected when it is transmitted in the pipeline, and the pressure value obtained by the water film pressure sensor in the test process will also be different from the pressure value at the real measuring point. In this paper, the mathematical model of pressure loss of L-shaped pipeline is established by theoretical calculation method, and the physical model of pipeline is established by using CFD computational fluid dynamics module. The relationship between dynamic and static factors and pressure loss is analyzed, the law of pressure change is obtained, the mechanism of pressure loss is studied. Finally, the test results are corrected. Because the physical properties of the liquid in the test pipeline, such as viscosity, temperature and specific heat capacity, This things have little effect on the pressure loss of the pipeline, these factors are ignored in the numerical simulation. The flow chart of pipeline pressure loss mechanism in water lubricated bearing system is shown in Fig. 3. The methods are as follows: 1) to establish the theoretical mathematical model of the pipeline, 2) to establish the
physical model of the pipeline, and to establish the physical model of the pipeline. 3) mesh the established model, set the boundary conditions, and select the relevant algorithm of fluid calculation; 4) The relevant output control attributes are set and relevant variables are set, and the parameters of the water lubrication bearing system pipeline are monitored and analyzed after the iteration is started to obtain the pressure loss-related mechanism.

3. Model establishment

3.1 Mathematical model of pipeline pressure loss
According to the mechanism and manifestation of the energy loss in flow, the pressure loss can be divided into the pressure loss along the path and the local pressure loss. The pressure loss along the flow process refers to the flow loss caused by the viscous friction between the processes along the flow path. The mechanical energy consumed by the fluid to overcome the friction force along the flow process is called the energy loss along the way. According to the knowledge of fluid mechanics and Darcy's formula, the formula of pressure loss along the way can be written as shown in formula (1).

\[ h_f = \lambda \frac{l}{d} \times \frac{v^2}{2g} \]  \hspace{1cm} (1)

\[ v = \frac{4q}{\pi d^2} \]  \hspace{1cm} (2)

In formula (1), \( \lambda \) is the resistance coefficient along the way, which is related to the flow state (laminar flow or turbulence), Reynolds number and the roughness of the pipe wall, while for the L-shaped pipeline, assuming that it is a hydraulic smooth pipe, then \( \lambda \) can be obtained by formula (3).

\[ \lambda = 0.3164 \text{Re} - 0.25 \]  \hspace{1cm} (3)

Joint formula(1), (2), (3) can be used to obtain pressure loss \( h_f \):

\[ h_f = \frac{8lq^2}{gd^5 \pi^2} \times \lambda = (0.3164 \text{Re} - 0.25) \times \frac{8lq^2}{gd^5 \pi^2} \]  \hspace{1cm} (4)

Local pressure loss refers to the flow loss caused by local obstacles in the process of fluid flow. For L-shaped pipe, there is local pressure loss at the bend. According to the knowledge of fluid mechanics, the calculation formula of local pressure loss is as follows:

\[ h_f = \xi \frac{v^2}{2g} \]  \hspace{1cm} (5)

The local resistance coefficients given in the existing literature are all measured under turbulent conditions. For 90° pipe, the calculation of the local drag coefficient under other turbulence conditions should be calculated according to the resistance coefficient along the path and equation.

\[ \xi = \xi_0 \frac{\lambda}{0.022} \]  \hspace{1cm} (6)

The simultaneous expressions (2), (5), (6) can be used to derive the local pressure loss of the pipeline:
\[ h_j = 419 \frac{q^2}{\pi d^2 g} (0.3164 \text{Re} - 0.25) \]  

Among them, \( h_j \) - the pressure loss along the way;

\( l \) - pipe length;
\( q \) - the flow, unit in the pipeline;
\( d \) - pipe diameter;
\( v \) - liquid flow rate;
\( \xi \) - local resistance coefficient;

\( \Delta p \) - total pressure loss of the pipeline system, unit;

\( \text{Re} \) is the Reynolds number.

### 3.2 Pipeline physical model

When modeling, the structure such as fillet, chamfer and so on is ignored, and the calculation domain of pipe in the rotation axis is created. The hexahedral element grid is used to divide the single pipe (pipeline 6), and the tetrahedral unstructured grid is used to divide the whole computing domain. As shown in figure 2, the number of nodes and units in a single pipe grid is 552883 and 578048 respectively. After the rotation axis is Boolean, the number of nodes in the computational fluid network is 110536 and the number of cells is 562531. Because the temperature change of water flows in the bearing system is small, the influence of temperature on the pressure loss of water lubricated bearing system is not taken into account.

The properties of the fluid in the pipe are set as follows: the temperature is 298K, density is\( 998 \text{kg/m}^3 \), the dynamic viscosity is\( 0.001 \text{Pa} \cdot \text{s} \), the inlet boundary is set as the velocity inlet, the turbulence intensity is set as 5, the hydraulic diameter is set as 4, the outlet condition is set as the free flow outlet, and the pipeline wall in the water lubricated bearing system is set as the non-slip wall. At the same time, the rotating speed of the pipe is set, and the different rotating speed is given. In water lubricated bearing system, the radius of shaft diameter is 50mm, and The gap ratio is \( c/R=0.008 \), The change range of speed spindle \( w \) is 47~200Rad/s, from the Taylor criterion, the fluid is turbulent. In the water lubricated bearing system, the fluid motion in the pipeline and the rotation of the pipeline itself are
from the practical engineering point of view, so the turbulence model is selected as the standard turbulence model RNG $k-\varepsilon$, select water-liquid in material set up, density is $998 \text{kg/m}^3$, Viscosity is $0.001 \text{Pa.s}$, the pressure-velocity coupling algorithm is selected to solve the SIMPLE algorithm.

4. Simulation results and analysis

4.1 Effect of different rotating Speed on pressure loss of Pipeline

In order to explore the effect of different rotating speed on the pressure loss of water film, the longest pipe 6 was taken as the object. By changing the rotation speed of the shaft, it means that the speed of the pipe is $84 \text{rad/s}$, $126 \text{rad/s}$, respectively, the influence of different rotating speed on the distribution of pipeline pressure loss is analyzed. The results are as follows:

(a) Static pressure cloud diagram at $84 \text{rad/s}$

(b) Static pressure cloud diagram at $84 \text{rad/s}$

Figure 3. Pressure cloud map at different speeds

It can be seen from figure 3 that when the liquid in the pipeline flows at different rotating speed and the same speed, the pressure value at the entrance of the pipeline is the maximum, and the pressure of the radial pipeline decreases evenly along the radial direction, and there is no obvious sudden change. At the turning point of the L pipeline, due to the rotation of the pipeline and the fluid itself, the pipeline is affected by gravity, flow resistance, centrifugal force, coriander force caused by rotation, and the direction of velocity changes instantly in the local area, as a result, the fluid is gradually dumped near the outer wall, resulting in a large number of fluids being squeezed to the outer wall, the lateral pressure is higher than the inner pressure, and a vortex of different sizes is formed in the local area, and the vortex is produced. It is easy to be subjected to hydraulic impact, which leads to relatively large pressure loss and energy loss in the local area, resulting in changes in fluid viscosity, temperature and other properties. After the fluid reaches the horizontal pipe section, it advances in a stable form. As the distance between the local part of the pipeline and the exit is farther, the pressure loss value in the pipeline will be reduced. At the outlet of the pipeline, the pressure value in the pipeline is negative. The phenomenon of reflux shows that the pressure in the pipeline is continuous. At the same time, the decrease of pressure in the pipeline increases the resistance of liquid flow and promotes the liquid in the pipeline to flow forward.

4.2 Influence of different flow rate on pressure loss of Pipeline

The flow rate of the pump is $3.5 \text{m}^3/\text{h}$. The velocity of liquid in water lubricated bearing is the ratio of the flow value of pump to the cross section of pipeline inlet. In order to study the influence of different inlet flow value (velocity value) on the pressure loss of water film, By changing the velocity value at the entrance, that is the pipeline velocity values are $20 \text{m/s}$, $25 \text{m/s}$ respectively, the influence of
different flow rate (inlet velocity) on the pressure loss distribution of the pipeline is analyzed, and the results are shown in figure 4.

As can be seen from figure 4, the greater the flow rate (inlet speed) in the pipeline, the more the pressure decreases along the way. The fluid in the pipeline is always subjected to gravity, flow resistance, centrifugal force, and the Coriolis force produced by the pipe during rotation. When the liquid just enters the pipeline, the centrifugal force in the pipe is greater than the Coriolis force, resulting in a drop in the pressure in the pipeline. In the local part, the liquid in the pipe is caused by the double action of self-rotation and pipe rotation, which leads to the inconsistency of the internal and external pressure, resulting in the vortex, which is easy to cause vibration and noise in the local part. The horizontal straight pipe section, due to the rotation of the pipe, the direction of centrifugal force, the direction of flow resistance, and the direction of velocity, the change leads to the fluctuation of the pressure value in the pipeline. The larger the velocity of flow, the smaller the resistance, the smaller the velocity of liquid flow, the greater the resistance, the more pressure loss is caused in the horizontal straight pipe than the local pressure loss, and the higher the inlet flow rate is, the more the pressure loss is caused by the horizontal straight pipe, and the higher the inlet flow rate is. The larger the pressure value at the outlet of the pipeline is, the more the reflux occurs at the outlet, and the loss of the pressure value at the outlet increases accordingly.

4.3 Effect of different sizes on pressure loss of Pipeline

In order to study the influence of six pipelines of different sizes on the pressure loss of the pipeline, the idea of control variable method is used to analyze the pressure loss of the pipeline. The reference conditions of the parameter setting are as follows: the rotational speed is 480 r/min, the pressure of water supply is 0.25 MPa, the pressure based solver is selected, the transient simulation is selected, and the RNG is selected. In the turbulence model, the velocity inlet is selected, the turbulence intensity is 5, and the velocity at the entrance is 5 m/s the rated velocity at the test. The temperature is 298 K, hydraulic diameter is 4 mm, the exit is set to the free flow exit, and the rotating area is set to rotate at the speed of 480 r/min (50 rad/s), the center of rotation is (0, 0, 0), and the direction of rotation is clockwise around the Z axis. The wall area is set to a non-slip wall, and the absolute velocity is set to 5 m/s, the speed is set to 50 m/s, the SIMPLE algorithm is selected and the second order upwind scheme is selected.

At the rotating speed of 480 r/min, the pressure of water supply is 0.25 MPa, not in the external load, The flow rate at the rated entrance is 5 m/s. The pipe pressure cloud diagram of different sizes is
shown in figure 5 (a). From figure 5 (a), figure 5 (b), it can be seen that the influence values of different sizes on the pressure loss of the pipeline are different without external load. The longer the pipeline, the pressure loss of the greater value, in the local bend pipe, the pressure value decreased trend of local area is larger, and the lateral pressure is greater than the inside of the pressure value in local place, because in the local place the direction and the rotation of the rotor speed in pipeline direction constantly change, caused by the changing of fluid pressure value in the pipe. It is calculated that the pressure loss value of outlet pipe 1 is $4.5 \text{KP}a$. Pipe 2 pressure loss value is $1.870 \text{KP}a$. Tube 3 pressure loss value is $4.30 \text{KP}a$. The pressure loss value of pipe 4 is $5.23 \text{KP}a$. The pressure loss value of pipe 5 is $6.037 \text{KP}a$. The pressure loss value of pipe 6 is $7.25 \text{KP}a$.

(a) Overall static pressure loss  
(b) Local pressure changes at different sizes of pipes

5. Test result correction

In the case of simulation, from the simulation of the whole pipeline, we can see that the pressure value in the pipeline begins to drop from the entrance, and then the pressure value in the pipeline begins to have reflux in the horizontal stage, and the reflux pressure is larger in the vertical. The opposite changes of vertical pipe and horizontal pipeline in different parts ensure that the water-lubricated bearing system tends to a dynamic stable process in the case of rotation. The mathematical statistical method is used to calculate the ratio between the entrance and outlet sections of pipeline 4 and pipeline 6, respectively, and then the ratio between inlet and outlet is calculated by means of mean value. The specific methods are as follows: the average pressure on the surface at the section of pipe 4 and pipe 6 is obtained by using the area setting panel (Surface Integrals) in node Reports of the model tree, and the report type (Report Type) is selected as the surface average pressure (Area-weighted Average). The inlet (in4) and outlet (out4) of pipe 4, the inlet (in6) and exit (out6) of tube 6 are selected respectively, and the average pressure values of inlet and outlet sections are obtained, respectively, and the report type (Report Type) is selected as the surface average pressure (Area-weighted Average). The inlet (in4) and outlet (out4) of pipe 4, the inlet (in6) and outlet (out6) of pipe 6 are selected respectively, and the average pressure values of inlet and outlet sections are obtained respectively. By calculation, the proportional coefficient of outlet and entrance of pipe 4 is 0.63, which is the same as that of pipe 4. Use the same approach to manage By calculating the coefficient of channel 6, it can be concluded that the ratio of pressure coefficient between outlet and inlet of pipeline 6 is 0.711, and then the pressure value at the point measured by the real sensor with
pressure coefficient is drawn, That is, the test results of the full cycle distribution of water film pressure in the radial section of rubber bearings with eight grooves and concave surfaces at the real measuring point (in the case of pressure loss), the pressure unit is kPa, load unit is N. Figure 6(a), figure 6(b) is the true real value of pipeline 4 and pipeline 6, respectively.

(a) Water film pressure distribution over the entire circumference of tube 4 after calibration

(b) Water film pressure distribution over the entire circumference of tube 6 after calibration

Figure 6. Water film pressure distribution over the entire circumference of tube 4 and 6 after
From figure 6(a) and 6(b), it can be found that there is still a difference between the simulation and the test, and there are some errors. When the load is 500N and 1000N, and the shaft speed is 480r/min, water supply pressure is 0.25MPa; the water film pressure in the pipeline is redistributed, the pressure in the pipeline changes regularly along the axial direction. Through the experimental correction results, it can be seen that there is a large pressure between each strip and the groove, and the reason for this change is that there is a pressure loss in the pipeline. There is a large and small water film between the laths (shown in the concave area of the figure), that is, the pressure value on the plate appears in the center of the lath. From the results of figure 6(a) and figure 6(b) after modifying the water film pressure, it can be seen that the water film pressure in the pipeline also forms a pressure peak, which makes different parts of the lath bulge and forms a water capsule, resulting in the formation of fluid pressure. However, the pressure value in the pipeline is in a kind of dynamic change, and the pipeline reflux phenomenon appears in the horizontal part of the pipeline, but at this time, the pressure value in the pipeline is larger in the vertical. It is shown that the dynamic change process leads to the existence of pressure difference in the pipeline, resulting in the energy loss in the pipeline and the pressure loss in the pipeline.

6. Conclusions
In order to solve the problem of pressure loss in wireless monitoring of water film pressure of water-lubricated bearings, the mathematical model and physical model of pipeline pressure loss are established, the mechanism of water film pressure loss of L-shaped pipeline is studied, and the test results are corrected. The conclusions are as follows:

(1) The factors affecting the pressure loss of water film are the flow rate of liquid, the rotating speed of rotating shaft, the length of diversion hole in the design of rotating shaft, and the dynamic and static state of the rotating shaft. Because of the pressure loss of the rotating shaft in the process of rotation, it is easy to have the pressure difference at the corner. The axial water film pressure shows a downward trend, and it fluctuates obviously in the middle of the rotating shaft. This is because there is pressure loss in the rotating process of the rotating shaft, at the same time, the internal and external pressure difference is easy to occur at the corner of the rotating shaft, and the vibration and noise of the pipeline are easy to produce. Secondly, there will be liquid reflux near the monitoring point of the sensor.

(2) The speed, velocity and size of the pipeline will cause the pressure loss in the pipeline, and the larger these parameters are, the greater the pressure loss will be, and the pressure drop value in the pipeline will maintain a dynamic change process.

7. References
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