

Oil Flow Simulation Based on CFD for Reducing Agitation Torque of Ball Bearings

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ABSTRACT

Agitation torque associated with oil lubricant is one important factor of torque loss in bearings under sufficient lubricating conditions. So far, efforts on reducing agitation torque were taken mostly by means of conventional experimental trials. Aiming for speedy, low-cost development, a calculation program for predicting the amount of agitation torque and oil distribution tendency in rolling bearings has been developed using computational fluid dynamics (CFD) analysis.

At first, since rolling bearings are axially symmetric, sector models of bearings were adopted. To verify the method, torque losses and oil quantities in ordinary-sized bearings have been measured. Calculated values based on sector models are qualitatively in good agreement with measured results. The difference between the absolute values of measured and calculated torque may be caused by the difference between the vertical model used in CFD analysis and the horizontal torque-testing rig used in measurement.

To improve the accuracy, full models of the bearings have been developed and verified by experiment. The measured values are about 1.1 times as high as the calculated ones. It seems reasonable that this method can predict the agitation torque quantitatively in practical accuracy.

Using this technique, the influence of bearing cage shape on oil flow and agitation torque has been reliably investigated, resulting in further development of low-torque ball bearing. Oil flow in this bearing is controlled and optimized by specially designed plastic cage. Thus, agitation torque is reduced significantly in comparison with conventional products.

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INTRODUCTION

In efforts to address the issue of global warming and energy conservation, automobile manufacturers are improving the fuel economy of vehicles for the purpose of reducing CO₂ emissions and fossil fuel consumption. Therefore there is a growing need to reduce torque losses in bearings that support power transmission gears in automotive transmissions and differentials [1].

For torque reduction, bearing manufacturers have been focusing on rolling and sliding friction losses. The roughness and shape of raceway surfaces and sliding contact surfaces were optimized using kinematic performance analysis of bearings [2, 3, 4]. In such analysis, the rolling torque is estimated by kinetic friction equations considering EHL rolling resistance [5]. Instead of iron cages, plastic cages began to be used in bearings to reduce sliding friction losses because of its

lightness and low friction characteristics [6, 7]. However, losses that are caused by lubricant churning resistance were seldom taken into consideration. While great reductions in rolling and sliding torque are achieved, agitation torque becomes an important factor of the total torque losses in bearings, especially under sufficient lubricating conditions.

So far, to reduce lubricant churning resistance, the internal design of rolling bearings has been optimized by use of trial manufacture and experiments, which requires plenty of time and big costs. For improving the efficiency of development of low-torque bearings, oil flow simulation based on CFD can be considered a good solution. Using CFD simulation to calculate the agitation torque of bearings is an economical and convenient way for investigation. J. Reichert [8] developed a calculation method of agitation torque using CFD. But in this method, the model of bearing was simplified and the space

between cage and outer ring was not considered. Aiming for greater accuracy and faster product development, a method of prediction of agitation torque and oil distribution tendency in all parts of bearings was developed using oil flow simulation.

At first, since rolling bearings are axisymmetric, sector models (including an integral roller/ball) of bearings in vertical posture are preferred in order to reduce calculation costs. However, sector model should be applied under axially symmetric conditions which include not only the geometry condition but also the force condition. Therefore in a sector model, the direction of gravity has to be set along the rotational axis. When bearings are used on horizontal shafts, like in cars, the sector model may not reflect the distribution and the motion of the oil flows inside the bearings precisely. As a result, measured and calculated values of torque fail to quantitatively match with each other.

To improve the accuracy of the oil flow simulation, full models of the bearings have been developed and established in this paper. With this improved analysis method, the influence of bearing cage design on oil flow and agitation torque was investigated, resulting in further development of low-torque ball bearings.

1. OIL FLOW SIMULATION TECHNIQUE

Generally in CFD calculations of agitation torque, single-phase flow model and steady state of flow with an assumption of constant velocity are preferred in order to save calculation time. However, in reality, lubricant oil and air are stirred by rolling elements and form free surface flows within bearings [9]. To precisely simulate this kind of flow in detail, a gas-liquid multi-fluid model with the SIMPLE transient solution algorithm was adopted in this work. The following assumption applies to this multi-fluid model: all fluids present in a given control volume share the variables computed for the fluid mixture. These are obtained by solving transport equations for velocity, pressure, temperature, etc. Although it is a transient model, it is also suitable for steady-flow problems by computing until a steady-state solution is reached. The fully implicit Euler scheme is used as the temporal discretization scheme for this model.

For tracking and locating the free surface with high accuracy, the volume-of-fluid (VOF) method was used. In order to maintain the interface sharpness of free-surface flows, the convective terms in the volume fraction equations were computed using the High Resolution Interface Capturing (HRIC) scheme [10].

Since the lubricant oil flow may move due to the force of gravity, especially near the outlet of oil, the gravitational body force and buoyancy effects are considered in this simulation model. The information needed to assemble the pressure and gravity forces on the right-hand-side of the momentum equation is specified according to the reality.

As the calculation capability is limited, it is required to simplify the CFD model. As mentioned above, the EHL rolling resistance is already taken into consideration in the calculation of rolling torque of bearings. So in CFD analysis, the EHD film and the lubricating situation between rolling elements and raceway are ignored.

Based on a general-purpose CFD tool, a program for calculating agitation torque and oil quantity distribution was developed and incorporated into the analysis software. In this program, the flow-induced resistance (i.e. agitation torque) on wall cell faces was computed using the following expression:

$$\vec{T} = \vec{R}_b \times (\vec{F}_t + \vec{F}_n) = \vec{R}_b \times \left(\tau_\omega \frac{\vec{v}_{par}}{|\vec{v}_{par}|} + p\vec{n}_b \right) A_b \quad (1)$$

where $\vec{T}$ is the agitation torque vector, $\vec{R}_b$ is the radius vector from the rotational axis to the center of a near-wall cell, $\vec{F}_t$ is shear force, $\vec{F}_n$ is pressure force, τ_ω is shearing stress, $\vec{v}_{par}$ is the velocity vector component parallel to the wall at the center of the cell, p is pressure, $\vec{n}_b$ is the outward-pointing unit vector normal to the wall, and A_b is the cell face area. Only the circumferential component of flow-induced force is considered in the calculation. The agitation torque of a bearing equals the sum total of the torque on wall cell faces.

In this paper, oil flow simulation of bearings was conducted using this program. The evaluation of discretization errors was accomplished by repeating the calculations while altering the mesh or time step and noting regions of appreciable change in the solution. This correction process continued until the changes fell to acceptable levels.

2. SIMULATION USING SECTOR MODEL OF BALL BEARINGS

2.1. Simulation Method

Since rolling bearing is axisymmetric with respect to the axis of rotation, it is possible to solve oil flow simulation in a single sector model (including an integral roller/ball) of the bearing. A sector model is made up of two axial planes containing the symmetry axis. These planes are declared as cyclic boundaries at which the flow repeats itself. Selected scalar variables are forced to be equal at corresponding faces on the two boundaries. Velocity components are also equalized in a local coordinate system. In this work, sector models of ball bearings were exploited to reduce the size of the computational mesh.

To simulate the rotational motion of the bearings, the mesh in the main solution domain around the bearings should be made to rotate at an angular velocity about an axis. Still, the mesh far from the bearings (e.g. the mesh near the inlet and outlet of oil) should maintain the same position to ensure the stability of the

multi-phase fluid of oil and air. Therefore, it is necessary to assign different angular velocities to different mesh blocks within the model. In this paper, relative mesh rotation was simulated by activating the Coriolis and centrifugal force terms in the transport equations of the mathematical model at cells within each specified mesh block. It is then possible to have multiple adjoining rotating blocks, each with its own rotational speed but without actually causing the mesh to rotate. The entire solution domain was treated as a single entity when solving the flow field equations. Cells across the interface were implicitly coupled. The solution equation coefficients and the source terms were adjusted to account for the differing rotations.

2.2. Experimental Verification

To verify the oil flow simulation method, torque losses of ordinary-sized bearings, such as those that are found in automotive differentials and transmissions, were computed using the program mentioned above. Then the calculated results were compared to measured values for verification. The measured results of agitation torque were estimated using the method shown in Figure 1. When oil amount is close enough to zero (equivalent to oil coating), the measured value of the running torque of the bearing may be considered the same as the sum of rolling and sliding friction torque. Hence, when oil amount is over zero, the measured torque minus the torque of zero oil amount equals the value of agitation torque. In the experiment, the temperatures of outer ring and inner ring of the bearing were carefully measured to make sure they did not exceed the set temperature even when oil amount is close to zero. In fact, the temperature of inner ring increased by less than 1.8% in the measurement time within 15 seconds. This is possible when the oil film on the sliding contact surfaces is thick enough.

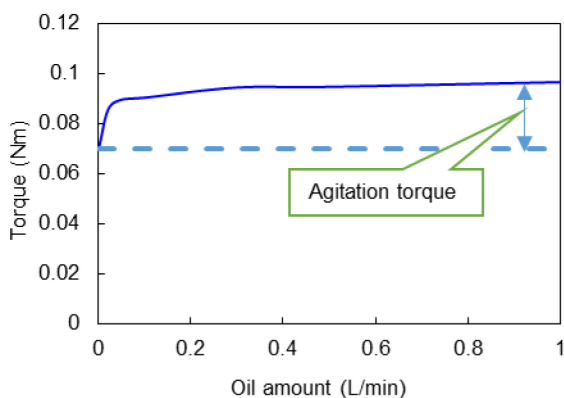


Figure 1. Running torque of ball bearing

The bearings used in the examination are presented in Figure 2. They have the same characteristics (which are shown in Table 1) except for the shape of the cages. Test conditions are listed in Table 2. The test rig used in the experiment is shown

in Figure 3. This equipment is designed for measuring the torque and temperature of bearings and oil flow observations for the evaluation of low friction bearings.

In the experiment, the test bearing was set in the test rig. Then the radial load and axial load were applied via hydrostatic bearings. And then the test bearing was rotated while oil was being supplied to the test rig. The moment of the outer ring was measured as the torque of the bearing with an arm and a load cell. The data from the experiment were recorded every 0.1 second. This includes the torque, the bearing (inner and outer ring) temperature, the oil (inflow and outflow) temperature, the oil flow rate and the rotating speed. Two experiments were done for one condition. In each experiment, the result of torque equals the average of 20 values, which were measured during the time when the temperature and torque was stable. The standard error of the torque values is less than 1.7% of the torque.

Figure 4 shows the relative value of the results of CFD simulation and experiment of the two bearings. In Figure 4, the result of Bearing A was set to be the reference value. (i.e., the agitation torque ratio of Bearing A was set to be 1.) Calculated results of torque ratio are qualitatively consistent with measured values. It seems reasonable that sector model can be used to evaluate the effect of shape improvements made to the bearings for reducing agitation torque. Therefore, we concluded that the oil flow simulation method can predict the tendency of agitation torque qualitatively with practical accuracy.

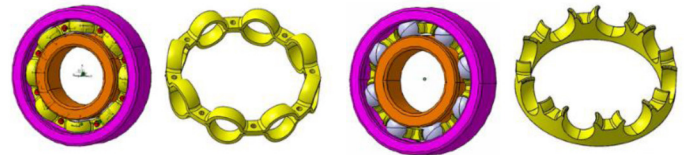


Figure 2. Ball bearings used in the experiment (left: Bearing A with an iron cage; right: Bearing B with a plastic cage)

Table 1. Characteristics of the bearings

Inner diameter	35 mm
Outer diameter	80 mm
Width	21 mm

Table 2. Test conditions

Rotation speed	3 000 min ⁻¹
Oil temperature	50°C
Oil viscosity	23.6 mm ² /s @ 40°C
Oil amount	0.1 L/min
Radial load	800 N
Axial load	100 N