Prediction of the Fluid Resistance in Stirred Fluid Using the Particle Method

Kazuo Muto¹, Isamu Sakai², Naoto Ozaki³

¹) Shizuoka Institute of Science and Technology, Mechanical Engineering
2200-2 Toyosawa, Fukuoka, Shizuoka, 437-8555 Japan (E-mail: kmuto@me.sist.ac.jp)
²) Fuji Technical Research Co., Ltd.
Queen’s Tower C 15F 2-3-5 Minatomirai, Nishi-ku Yokohama-shi Kanagawa 220-6219, Japan (E-mail: is_sakai@ftr.co.jp)

Received on July 1st, 2010
Presented at the JSAE Annual Congress on May 19, 2010

ABSTRACT: We carried out transient analysis of stirred fluid flow with rotating gear using the particle method (MPS method). The particle method is widely used as an effective technique for free surface flow and also easy to treat the moving boundary. In this research, we focused on the fluid resistance of gear and verified the correspondence with the experiments with two types of gear and two types of rotational rate. As a result, we found that the simulation value of stirring torque was consistent with experimental value in case of low rotational rate

KEY WORDS: CFD / Gear Box, Fluid Resistance, Particle Method

1. Introduction

Oil in a gearbox plays an important role in lubricating and cooling structural parts. On the other hand, it causes torque loss to occur due to fluid resistance, so it is necessary to take care concerning the quantity and quality of the oil used and also the selection of the profile of the casing wall (1). Even if the profiles of the case and the gear have been determined, the determination of the optimum oil surface height and also the physical properties of the oil with respect to the assigned profile is an issue. During the determination process, it is necessary to try out a number of patterns that have different driving conditions including speed, gradient, and atmospheric temperature.

In the above case, it is conceivable that if the behavior of the oil can be qualitatively and quantitatively predicted by numerical analysis, the design cost can be significantly reduced. However, to this end it is essential to validate the appropriateness of the analysis.

Accordingly, experiments and analyses using simple models (impeller model and gear model) which simulate the gearbox were carried out in order to clarify the extent to which the oil agitation phenomenon can be predicted by analysis. In this paper, particular attention was paid to stirring resistance as far as the gear, and a comparison between the calculated torque value obtained by analysis and the torque value obtained empirically using a torque gauge was made. The results are set out in Section 4

2. Experiment

The apparatus used in the experiment was a simplified one containing a single aluminum gear installed in a cylindrical acrylic case. The gear, torque gauge, and motor are directly connected to each other by the shaft. The gear is rotated by motor drive, and the torque value when the oil is being stirred is output in real time by the torque gauge (Fig. 1). The profile of the gear was validated by two models: an “impeller” model employing eight sheet-shaped blades, and a “gear” model in which a spiral groove was cut. The validation was carried out in two steps: 100 rpm, and 1000 rpm.

The oil used in the validation was commercially available differential oil. The physical characteristics of the oil at 30°C are as follows.

- mass density: 0.739 g/cm³
- kinetic viscosity: 450.5 cSt

The dynamic viscosity of the oil that was actually stirred using the test apparatus was measured using a viscometer. In the experiment, the temperature of the oil rose along with the passage of time. For the purpose of comparing this result with the analysis value, the timing at which the torque value was read was set several seconds before the point in time at which the oil temperature reached 30°C.,
From here on, the empirical torque value used was the raw measured value from which the torque value under the idling condition in which there was no oil was subtracted.

3. Numerical Analysis

The use of the particle method is effective for analyzing a fluid whose liquid surface undergoes large deformation, as in the case described in this paper. The particle method is a method of digitizing a space during numerical analysis. It expresses a continuum, such as a liquid, as a collection of particles. Each particle has pressure, speed, and other physical quantities as variables, and moves along with the current while retaining a constant mass. Because a calculation mesh is not used, this method has the advantage of facilitating the handling of free surfaces and moving boundaries. In this analysis, the MPS (Moving Particle Semi-implicit) method (2), which is a kind of particle method was used.

3.1. Outline of the MPS Method

The MPS method is intended mainly for incompressible fluids. It features the use of a semi-implicit algorithm in a time integral. One step in the calculation is roughly divided into the following three phases.

i. Updating the particle coordinates by explicit calculation
ii. Calculating the pressure value by implicit calculation
iii. Updating the particle coordinates by a pressure gradient

At stage i, the assumed coordinates of the particle are explicitly calculated according to gravitational force and viscous force. If the wall is to be moved, the updating of the wall position is carried out at the end of this stage. At stage ii, a Poisson equation of pressure is configured based on incompressible conditions, and this equation is solved in order to obtain the pressure value of each particle to be obtained. At stage iii, the coordinates of the particles are corrected according to the pressure gradient, and the final particle distribution is determined.

At stages i and iii, it is necessary to calculate the viscous force and the pressure gradient which act between the particles. These calculations are performed using an particle-particle interaction model of MPS method (2). At this time, the force acting on a certain particle is equal to the force resulting from the addition of a weighting factor and the interaction between that particle and a particle which exists within a certain range (effective radius) from it. There is no interaction between this particle and particles outside the radius of influence.

3.2. Outline of Torque Calculation

In the situation whereby an object that rotates about a fixed axis stirs the fluid, the torque \( \tau \) necessary for rotating the object can be expressed as follows.

\[
\tau = \tau_{\text{press}} + \tau_{\text{viscosity}} + \tau_{\text{inertia}} \tag{1}
\]

Here, \( \tau_{\text{press}} \), \( \tau_{\text{viscosity}} \), and \( \tau_{\text{inertia}} \) are the contributions to the torque due to the pressure, viscosity, and inertia.

Generally, a value that cannot be ignored is used as the value of torque \( \tau_{\text{inertia}} \) due to inertia. Here, however, the value of interest is the value of the torque generated during steady-state rotation of the model for the axis concerned. It was assumed as follows.

\[
\tau_{\text{inertia}} = 0 \tag{2}
\]

and also that it is not taken into account from the beginning of the calculation.

The torque \( \tau_{\text{x}} \) (\( x = \text{press} \), \( \text{viscosity} \)) due to pressure and viscosity is calculated as follows, based on the assumption that the rotor, which is considered to be a wall, is the reaction force applied to the fluid particles.

\[
\tau_{\text{x}} = \sum b_i \cdot (r_i \cdot F_{\text{x},i}) \tag{3}
\]

The suffix \( i \) indicates the index of the fluid particles which interact with the wall. \( \sum \) means that the sum of \( i \) is obtained. \( b \) expresses the unit vector in the rotating shaft direction, \( r_i \) expresses a vector which joins a point on the rotating shaft to a point on the wall which interacts with particle \( i \), and \( F_{\text{x},i} \) expresses the force which the wall applies to particle \( i \). \( \tau_{\text{press}} \) uses the calculation results at phase iii of the calculation step of the MPS method described in sub-section 3.1. In other words, the following relationship holds.

\[
F_{\text{press},i} = m_i a_i \tag{4}
\]

Here, \( m_i \) is the mass of particle \( i \), and \( a_i \) is the acceleration acquired by particle \( i \) due to the pressure gradient between particle \( i \) and the wall. \( \tau_{\text{viscosity}} \) uses the calculation results at phase i of the calculation step.

If the wall is a polygon, the part of the wall which interacts with particle \( i \) is assumed to be only the nearest neighbor polygon, and the point of action is assumed to exist in the position where the coordinates of particle \( f \) are projected onto the polygon (Fig. 2). The interaction between a fluid particle and the polygon is simulated by an interaction model which uses a wall weighting function (3). The wall weighting function indicates the magnitude of the effect of the polygon on the particle. This function causes the effect to decrease as the distance from the polygon increases, and become 0 when this distance exceeds a certain value. Consequently, the calculation of the interaction with the polygon need only be performed for fluid particles in the vicinity of the polygon.

3.3. Analysis Conditions

In the analysis, a particle model was used for the oil, and a polygon model was used for the case and gear. The rotational speed of the gear was increased linearly for a period of 0.5 second from the commencement of analysis, and was maintained constant thereafter. No-slip conditions were assigned between the wall surface and the fluid. In addition, the various conditions including the oil face height and the physical property values were made the same as those used in the test.
4. RESULTS

The Figure 3 (a) – (d) show snapshots of the oil behavior during the experiments and also during analysis. The analysis images correspond to the lapse of more than 2 seconds from the commencement of measurement. The number of rotations that the gear makes to this point is about two for (a) and (c), and about 20 for (b) and (d). The images obtained during the experiment correspond to the point where the oil temperature has reached 30°C, which occurs several minutes after the commencement of stirring. The stirred oil appeared cloudy. Because the cloudy oil becomes clear again if it is left to stand for several minutes, it is presumed that the cloudiness was the result of fine air bubbles becoming mixed with the oil when it was being stirred. Although the physical properties of the oil differed slightly according to whether or not the oil was cloudy, the physical property values for the cloudy condition were used in the analysis.

In the case of high speed rotation, it is difficult to make a comparison, however it was possible to confirm that the empirical values of the height and profile of the oil which collected at the bottom of the case agreed closely with the analysis values. On the other hand, it can be seen that the tendency of the oil to leave a trail and also to adhere to the acrylic case, which was found during the experiment, could not be repeated in the analysis. Figure 4 is a plot of the change with time of the torque value in the analysis. The data shown is the value (corresponding to Fig. 3 (d)) obtained from the analysis at 1000 rpm using the gear model. It can be confirmed that during the initial stage, the torque value rises along with the increase in the rotational speed, and that this tendency disappears after the lapse of 0.5 second when the rotational speed becomes constant. The average of the torque value between 1.5 and 2.0 seconds was 0.158 N-m, and the random variation in the torque value was about 0.02 N-m. The empirical values are shown in the figure for the purpose of comparison. However, because the empirical values are digital values which are recorded visually, only the average value and the range of the random variations in the vicinity were shown. The average torque value obtained empirically was 0.18±0.02 N-m in this case (gear model, 1000 rpm).

Table 1 shows the results of the torque values for all cases in which the experiment and analysis were carried out. The analysis values were averaged over the period between 1.5 and 2.0 seconds. It was confirmed both empirically and from the analysis that the impeller model produces a higher resistance value than that of the gear model, and also that the resistance value is higher at 1000 rpm than at 100 rpm. The deviation between the empirical and analysis values increased in proportion to the rotational speed. Particularly, in the case of the impeller mode, this tendency was prominent, and also the absolute value of the deviation was large.

5. OBSERVATIONS

Figure 5 shows the pressure distribution for case a (100 rpm) and case b (1000 rpm). The center part is a cut display to enable the pressure inside the fluid to be observed. The pressure in the display is the relative pressure, and the range of the contours is between 0 and 0.5 kPa. By observing the fluid on the side corresponding to the direction of advance of the blades, it can be seen that in case a, the pressure values from the vicinity of the blades to a free surface are, distributed uniformly, whereas in case b, the distribution is localized and the pressure pulsates in the vicinity. Temporally as well, it can be seen that in case a, the pressure distribution remains stable, whereas in case b, the pressure pulsates. The tendency for the pressure to pulsate at high rotational speed could also be seen between case c and case d. The pressure pulsations also affect the change in the torque value, and the random variations of the data shown in Fig.4 are the result of this change. Figure 6 shows the ratio between the torque due to pressure and the torque due to viscosity for case a and case b. The vertical axis has been scaled according to the average of all of the torque values between 1.5 and 2.0 seconds. From this it can be seen that the random variations in the torque due to pressure increase in proportion to the rotational speed. The standard deviation of the torque values in case b was four times that of case a. As a result, it is presumed that the increase in the error in the torque value is also caused by these pressure pulsations. The abovementioned pressure pulsations are non-physical, and also peculiar to numerical calculation. Improved algorithms which suppress the pressure pulsations of the MPS method have also been devised (4) (5), but they are not used in this analysis.

The torque value due to viscosity remained stable regardless of rotational speed. It is considered that torque...
Table 1 Torque value.

| case | model | rate [rpm] | \( \tau_{exp} \) [N \cdot m] | \( \tau_{sim} \) [N \cdot m] | error [%] |
|------|-------|------------|-----------------|-----------------|---------|
| a    | impeller | 100        | 0.095           | 0.079           | -17     |
| b    | impeller | 1000       | 0.215           | 0.378           | 76      |
| c    | gear    | 100        | 0.075           | 0.072           | -4.6    |
| d    | gear    | 1000       | 0.180           | 0.158           | -12     |

values were obtained with relatively high accuracy in cases c and d because the contribution of \( \tau_{viscosity} \) to the overall torque value becomes large. The ratio of \( \tau_{viscosity} \) with respect to the overall torque value was about 14% in case a, and this rose to 58% in case c. From the foregoing, it is considered that the accuracy of the torque value was poorest in case b because the proportion of the torque due to pressure in the overall torque value became large owing to the characteristics of the gear profile, and in addition the numeric pulsations due to high rotational speed affected the torque value.

6. Conclusion

As a result of numerical analysis performed using the particle method (MPS method), it was found that the stirring resistance value of the oil could be predicted to a certain extent by using a simplified gearbox model. Particularly, at low rotational speed (100 rpm), a value that was fairly close to the empirical value was obtained. Conversely, at high rotational speed (1000 rpm), the difference between the analysis value and the empirical value increased. It is considered that the worsening of the accuracy at high rotational speed is partly due to the fact that during analysis the pressure value of a fluid particle pulsed temporally and spatially, causing the random variations of the data to increase. Also, the error increased even in the case of a profile which caused the normal line of the gear wall surface to face the direction of motion. It is considered that this is because, in the overall fluid resistance, the effect of the pressure gradient became larger than the effect of the viscous force.

From the foregoing, it can be said that in the prediction of the resistance during fluid stirring using the MPS method, the
improvement of accuracy in the high rotational speed zone is an issue, and thus the stabilization of pressure calculation using the MPS method is an issue for the future.

References

(1) Automobile Technology Handbook 4 Design (power train), Society of Automotive Engineers of Japan.
(2) Seiichi Koshizuka: Particle method, Maruzen (2005)
(3) T. Harada, et al.: Improving of Wall Boundary Models for the MPS Method, Transactions of JSCES, No20080006, (2008)
(4) M. Kondo, S. Koshizuka: Suppression of Pulsations of Unnatural Numerical Values in the MPS Method, Transactions of JSCES, No20080015, (2008)
(5) M. Tanaka, T. Masunaga: Stabilization of the MPS Method and Smoothing of Pressure Utilizing the Effective of Pseudo-compressibility, Transactions of JSCES, No20080025, (2008)