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Investigations on lubrication characteristics of high-speed electric multiple unit gearbox by oil volume adjusting device

Shuai SHAO[1], Kai-lin ZHANG[1], Yuan YAO[1], Yi LIU[1], Jun GU[2]

[1]*State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China*

[2]*Suzhou Shon Cloud Engineering Software Co. Ltd., Suzhou 215100, China*

S1

In the MPS, the fluid region is discretized into a series of free-moving particles, and the physical quantities between particles are calculated by weighted average according to the distance. The kernel function defines the weight relationship of interaction between adjacent particles. The kernel function (Koshizuka and Oka, 1996) used in this paper is as follows:

$$w(r)=\begin{cases} \dfrac{r_e}{r}-1, & 0 \le r \le r_e, \\ 0, & r_e \le r, \end{cases} \tag{S1}$$

where, r_e is the maximum effective influence radius of particles and the influence scale of kernel function, and its size directly affects the number of interacting particles within the control radius. r is the actual distance between particles.

Particle number density is used to characterize the density of fluid particle distribution, reflecting the distribution of particles in the flow field. The weighted sum of the number of particles in the action radius is the number density of particles. The number density of particles i at $\boldsymbol{r}_i$ is defined as:

$$\langle n \rangle_i = \sum_{j \ne i} w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right), \tag{S2}$$

where, $\boldsymbol{r}_j$ is the instantaneous position of the surrounding particle j. Therefore, for incompressible fluid, this means that the particle number density n_i of the fluid needs to be maintained as the initial particle density constant n^0 during the calculation process.

The gradient of function φ at particle i can be obtained by weighted summing the gradient vector of particle i to the surrounding particles:

$$\langle \nabla \varphi \rangle_i = \frac{d}{n^0} \sum_{j \neq i} \frac{\varphi_j - \varphi_i}{\left| \boldsymbol{r}_j - \boldsymbol{r}_i \right|^2} \left(\boldsymbol{r}_j - \boldsymbol{r}_i \right) w\left(\left| \boldsymbol{r}_j - \boldsymbol{r}_i \right| \right). \tag{S3}$$

The diffusion term in the momentum conservation equation is expressed by Laplacian $\nabla^2\varphi$, and the Laplacian of particle i can be expressed by the physical quantity migration between the particle itself and its adjacent particles:

$$\langle \nabla^2 \varphi \rangle_i = \frac{2d}{\lambda n^0} \sum_{j \neq i} \left(\varphi_j - \varphi_i \right) w\left(\left| \boldsymbol{r}_j - \boldsymbol{r}_i \right| \right), \tag{S4}$$

$$\lambda = \frac{\int_V w(r) r^2 \mathrm{d}v}{\int_V w(r) \mathrm{d}v}, \tag{S5}$$

where, φ is the scalar value of particle physical parameters, d is the spatial dimension of the problem, λ is the correction factor.

S2

In general, when the MPS is used to analyze the flow field in the gearbox, the air in the gearbox is ignored, and only the lubricant region is filled with particles. Therefore, the particle number density near the free surface is very small, and the free surface particles can be captured based on this feature. In the MPS, the condition for judging whether particle i is a free surface particle is as follows:

$$\langle n \rangle_i^* < \beta \cdot n^0. \tag{S6}$$

When Eq. (S6) is true, particle i can be determined as a free surface particle. β is a discriminant parameter, which has a certain impact on the discriminant accuracy of free surface, and the general value is 0.8 ~ 0.99. The free surface discrimination method is shown in Fig. S1.

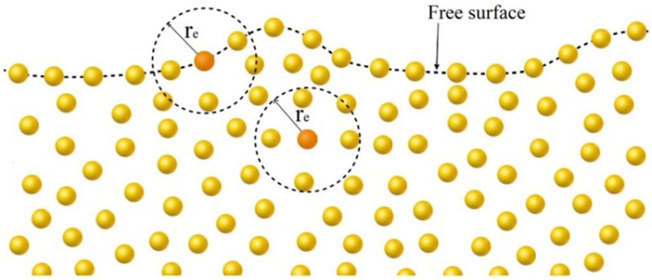

Fig. S1 Free surface discrimination schematic

In the MPS, the fixed wall is also simulated by particles. However, at the fixed wall, the problem of fluid particles missing often occurs, which makes the fluid particles near the boundary unable to obtain the correct integral interpolation. On the other hand, the internal fluid particles should be prevented from penetrating the wall. The method of arranging virtual particles is adopted in MPS: three layers of virtual particles are arranged, which are the first boundary particles of one layer and the second boundary particles of two layers. Among them, the first boundary particles will participate in the solution of pressure Poisson equation with fluid particles, while the second boundary particles only play a role in ensuring the integrity of the support domain. The boundary particle arrangement is shown in Fig. S2.

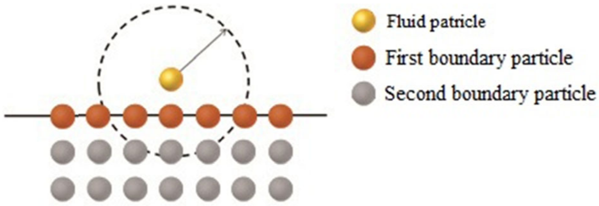

Fig. S2 Boundary particles schematic

S3

Due to the numerous components and complex structure of the gearbox, the lubrication characteristics of the gearbox mainly focus on the lubrication state of gears and bearings and the lubricant distribution of inner surfaces of the gearbox. Combined with the structure and working principle of the gearbox, the following measures are used to simplify the geometric model:

(1) Properly remove the chamfer, fillet and other unnecessary structure on the surface of the box, and retain the geometric characteristics of the inner surface of the box that affect the lubricant

distribution.

(2) Remove the bolts which have little effect on the lubricant distribution on the outer surface and inside of the box.

According to the components layout and working principle of the gearbox of high-speed EMU, a three-dimensional simplified model of the gearbox for lubrication characteristic analysis is established in SolidWorks 2016, as shown in Fig. S3. In the simplification of the gearbox model, the geometric structure and assembly relationship of the oil filling bolt, oil expulsion plug, magnetic plug, liquid level gauge, cleaning plug and breather assembly on the gearbox are completely retained, so that the above accessories can form a closed surface with the inner surface of the box to realize the granulation of the lubricant.

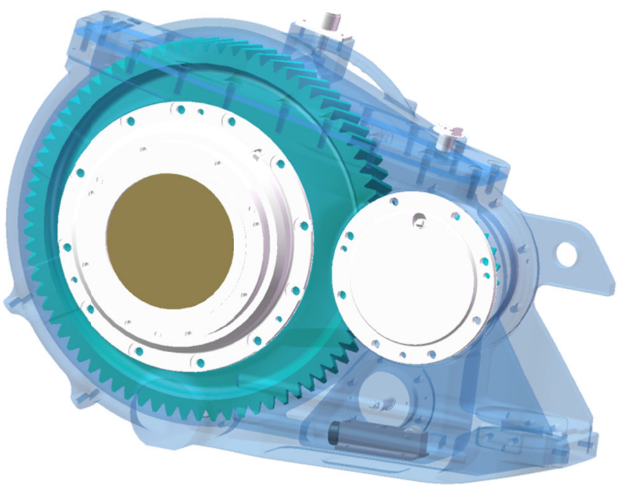

Fig. S3 Three-dimensional simplified model of high-speed EMU gearbox

When the EMU is running at high speed, the lubricant at the bottom of the gearbox is stirred by the rotational output gear and splashes to the input gear and bearings to complete lubrication and cooling. When the gearbox is running at low speed, the output gear needs to stir a lot of lubricating oil, so that enough lubricating oil can splash to the input gear and bearings. However, when the gearbox is running at high speed, the output gear only needs to stir a small amount of lubricant to meet the lubrication requirements. At this time, if the oil level is too high, the output gear will produce too much churning power loss, which will gradually increase the lubricant temperature and reduce the transmission efficiency. Therefore, the gearbox of EMU studied in this paper is equipped with an oil volume adjusting device at the bottom of the gearbox, which can dynamically adjust the oil immersion depth of the output gear according to the lubricant temperature, so as to adjust the lubricant quantity and power loss of each component in the gearbox.

References

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