Technology Explanation

Construction of CFD Analysis Technology for Internal Gear Pumps

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Abstract

The electrification of vehicles has accelerated the development of eAxle drive units from the viewpoints of energy saving, compactness, and low cost. The use of hydraulic pumps in these eAxle units is diversifying, and demand for cooling and lubrication applications is increasing. On the other hand, hydraulic pumps used in automobiles are required to be more efficient and quieter from the viewpoints of energy conservation and low noise. To meet these performance requirements, design strategies based on theory and phenomenology are necessary, and CFD (Computational Fluid Dynamics) analysis technology has been used to predict pump flow characteristics and optimize pump design.

In this paper, we focus on the flow characteristics of an internal gear pump and confirm the prediction accuracy of CFD analysis technology. The causes of flow reduction are mentioned, and a highly accurate prediction technique is obtained by considering crevice leakage, bubbles, and cavitation. In addition, a case study of the application of this technology to a development project of engineering department and its improvement is reported.

1 Introduction

The automotive industry has promoted the electrification of vehicles as an environmental measure and has accelerated the development of eAxle drive units from the viewpoints of energy saving, compactness, and low cost. The eAxle unit is a package product consisting mainly of gears, motors and inverters, in which oil is often used to lubricate the gears and cool the motors. The oil is supplied by hydraulic pumps for lubrication or cooling. KYB is currently developing an internal gear pump for these lubrication and cooling applications. Similar to the drive units, these internal gear pumps are required to be energy saving (higher efficiency of pumps). In addition, the pumps themselves need to be even quieter, in line with the trend towards low-noise vehicles due to electrification. In response to these requirements, various measures are taken, including reducing pressure loss due to fluid resistance, reducing crevice leakage, adjusting the timing of port operation, and stabilizing internal pressure. To meet even higher performance requirements, design strategies based on theory and phenomenology are necessary. KYB uses Computational Fluid Dynamics (CFD) analysis technology. Focusing on the flow characteristics of internal gear pumps, this paper explains the analysis technology for internal gear pumps based on the flow characteristics of hydraulic pumps, along with a case study of applying the technology to an internal gear pump development project.

2 Analysis

2. 1 Flow Characteristics

Fig. 1 is a graphical representation of the speed-flow characteristics of common hydraulic pumps. The dashed line shows the theoretical discharge flow, and the solid line shows the actual discharge flow. The theoretical flow of a hydraulic pump is calculated from the displacement and speed of the pump and is therefore proportional to speed. In reality, higher speed results in higher flow loss. This flow loss is dominated by the loss due to internal leakage up to a certain speed level: the theoretical flow is reduced by the same amount as the leakage loss ([1]). As the speed continues to increase, the internal flow rate increases, causing local pressure drops in the suction line and pump chamber. These contribute to larger bubbles in the oil and the occurrence of cavitation to reduce the ratio of oil volume to suction volume, resulting in a significant reduction in flow ([2], [3]) [1].

The ratio of theoretical flow to actual flow is called volume efficiency, which is used as a measure to evaluate the efficiency of hydraulic pumps. Therefore, one of the approaches to increase pump efficiency is to increase the volume efficiency, in other words, reduce the flow loss.

KYB designs and analyzes hydraulic pumps considering [1] through [3] in Fig. 1, which are the major causes of flow loss.

[1] Crevice leakage inside the pump

A hydraulic pump, which has rotating and oscillating motions, has clearances between its parts to prevent seizure. These clearances can be passages for the fluids, including the flow of oil from the suction port to the discharge port caused by pumping and the flow of oil circulating inside the pump through the clearances. Therefore, the suction flow is reduced by the same amount as the internal circulation flow to become the discharge flow, resulting in lower volume efficiency.

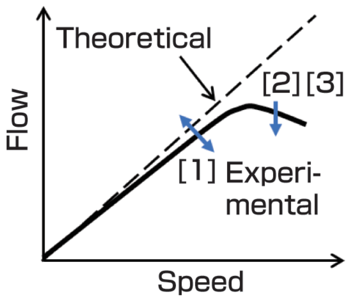

Fig. 1 Speed-flow characteristics

In addition, when high-pressure oil enters the low-pressure zone due to internal leakage, the pressure pulsation is exacerbated, causing a noise problem. Therefore, the clearances, which are essential to prevent seizure and can cause lower volume efficiency and noise problems, must be properly designed to prevent seizure and reduce leakage.

[2] Bubbles in the oil

Fig. 2 shows a visualized section of the suction oil passage of a vane pump. The white dots in the oil passage represent bubbles contained in the hydraulic oil. These bubbles are created when the hydraulic oil is mixed with air during oil mixing or tank oscillation in the hydraulic circuit and have flown into the pump. For example, in the continuously variable transmission (CVT) system, which is used to continuously change the gear ratio of an automobile, it is said that 10% to 30% or more bubbles are contained in the hydraulic fluid in the hydraulic circuit.

These bubbles in the oil swell as the pump speed increases to produce a higher flow, resulting in a lower fluid pressure. The pump is now unable to deliver as much flow as the volume of the swollen portions of the bubbles, resulting in a lower discharge flow rate. These larger bubbles can also cause vibration, noise, and equipment damage, and reduce the apparent stiffness of the oil. They can reduce system responsiveness [2].

[3] Cavitation occurring in the pump

Fig. 3 shows a visualized section of the pump chamber of a vane pump. The white areas in the pump chamber represent bubbles due to cavitation. This cavitation occurs, when the fluid pressure is below the saturated vapor pressure due to higher flow velocity inside the pump or other reasons the fluid vaporizes and bubbles form. As in case [2], the pump can no longer deliver as much flow as the volume of the bubbles formed, resulting in a lower discharge flow rate. This can cause equipment damage due to erosion. It is therefore important to suppress cavitation [2].

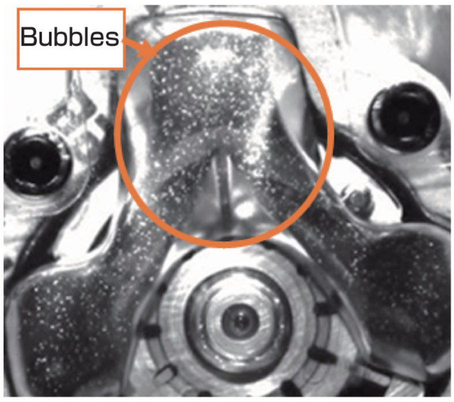

Fig. 2 Bubbles in the hydraulic fluid

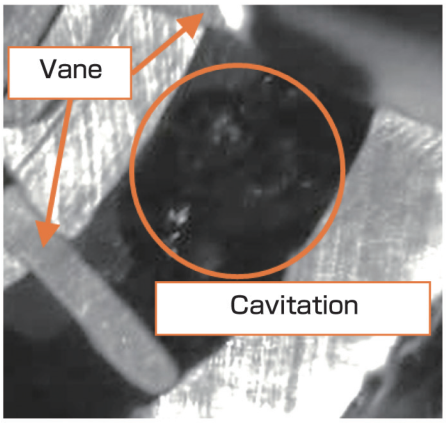

Fig. 3 Cavitation caused by pumping

Therefore, to accurately predict the flow characteristics of an internal gear pump, which is a positive displacement pump like the vane pump, it is necessary to reflect the clearances in the analysis model, consider the mixed flow, and formulate the cavitation phenomenon.

2. 2 Target Internal Gear Pump

Fig. 4 shows an overview of the parts of the internal gear pump used in this paper. The rotor assembly, consisting of an inner rotor, an outer rotor, and a shaft, is sandwiched between the body and cover. The inner rotor has six teeth, and the outer rotor has seven teeth. In the internal gear pump, as the inner rotor rotates, the outer rotor rotates to create a gear mesh that forms the pump chamber. The increase or decrease in volume of the pump chamber provides the pumping action. The volume of the pump chamber is minimum just before the suction port and increases in the area of the suction port, allowing oil to enter the chamber. The pump discharges the oil as the volume of the pump chamber decreases in the discharge port area (Fig. 5).

2. 3 Analysis Conditions

The analysis was performed using commercially available Simerics MP+® software (Simerics Inc., USA). Fig. 6 shows an example of a computational grid for the fluid part of the internal gear pump. Since the shape of the pump chamber changes from moment to moment with rotation, the size of the computational grid also changes accordingly. The shape of the pump chamber for the maximum and minimum mesh size is shown in Fig. 7.

Table 1 summarizes the analysis conditions. The calculation was performed considering the mixed flow of oil and gas. The total computational grid consists of about 400,000 cells. The pump chamber uses a fine mesh to accommodate dramatic changes in its volume and occupies about 50% of the total number of cells.

To consider internal leakage in the internal gear pump as well, the clearance between the inner and outer rotors (hereinafter, “tip clearance”, in Fig. 8), the clearance between the cover or body and each rotor, and the clearance between the outer rotor and the circumference of the body (hereinafter, “side clearance” and “body clearance”, in Fig. 9) were added to the analysis model.

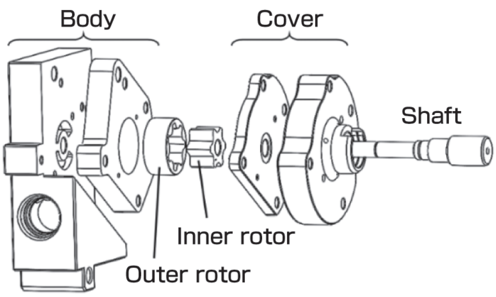

Fig. 4 Components of internal gear pump

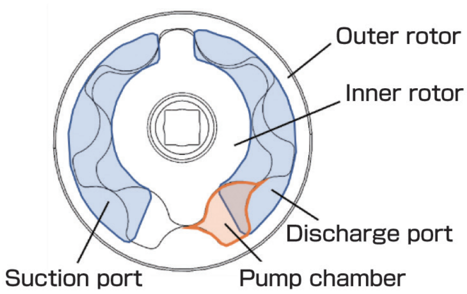

Fig. 5 Rotor parts names

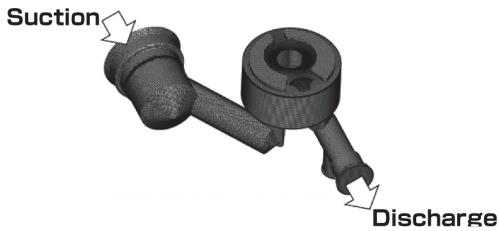

Fig. 6 Computational grid

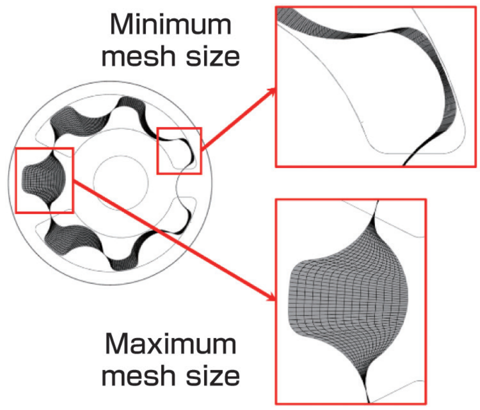

Fig. 7 Moving boundary of pump chamber model

2. 4 What to Adjust for Internal Gear Pumps

In order to perform the CFD analysis of internal gear pumps considering the flow losses mentioned above, the analysis model settings and analysis conditions were adjusted. The adjustment items are described below:

Table 1 Analysis conditions list

Fluid parameter			
Oil	Temperature	100	℃
	Density	786	kg/㎥
	Viscosity	0.0048	Pa・s
	Bulk modulus	1.52	GPa
	Vapor pressure	400	Pa (Abs.)
Gas	Density	0.94	kg/㎥
	Viscosity	2.194×10^{-5}	Pa・s
Boundary conditions			
Suction pressure		0	MPa (Gage)
Discharge pressure		0.2, 0.5	MPa (Gage)
Rotation speed		1000, 3000, 5000	—

Fluid model		
Two-phase flow	Homogeneous medium model	
Viscosity	Laminar flow model	
Grid		
Moving boundary	Sliding mesh	
Pump chamber	Hexagonal lattice	
Other	Tetrahedral lattice	
Minimum cell size	1×10^{-5}	m
Total number of cells	Approx. 400,000 cells	
Computation		
Time	1.5 to 2 days	

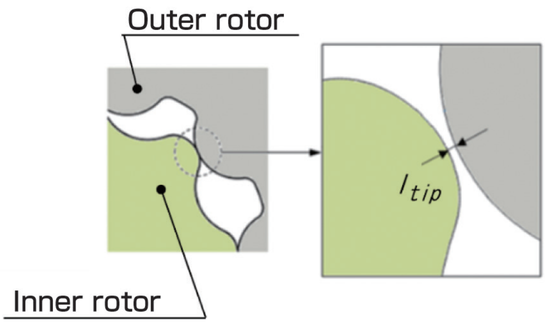

Fig. 8 Tip clearance

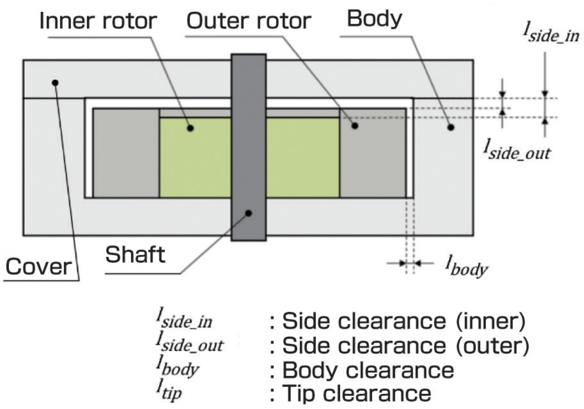

Fig. 9 Side and body clearances

[1] Cavitation model

A numerical model called the Singhal model was used in the analysis to represent cavitation phenomena. This model takes into account the liquid-vapor phase change and the effect of non-condensable gases, which allows for the representation of vapor generation and disappearance and gas transport [3]. R_e and R_c in equation (1) are coefficients related to vapor generation (evaporation) and disappearance (condensation). KYB has set these coefficients to appropriate values for hydraulic fluid to improve accuracy. However, we performed the calculation with a constant mass fraction of gas bubbles contained in the oil, without considering the precipitation of dissolved air and the expansion and contraction of the bubbles. We then adopted the Singhal model, which had been improved to account for these factors, to further improve accuracy.

(Equation for liquid-vapor phase changes; partial extraction)

$$\frac{\partial(\rho f_v)}{\partial t} + \nabla \cdot (\rho \vec{V} f_v) = \nabla \cdot (\Gamma \nabla f_v) + R_e - R_c \qquad (1)$$

ρ : Liquid mixture density
f_v : Vapor mass fraction
$\vec{V}$: Computational grid volume
Γ : Equation of diffusion phenomenon
R_e : Vapor generation rate
R_c : Vapor disappearance rate

[2] Clearance setting

Clearance settings, which are often set using design dimensions as a reference, are such small values that they can be significantly affected by the dimensional accuracy of the analysis model. An example of this for internal gear pumps is the interaxis distance between the inner and outer rotors. The internal gear pump discharges oil as the outer rotor rotates while the inner rotor rotates as described above. If the axis-to-axis distance is out of specification, this misalignment is a tip clearance error. If this error exceeds the minimum tip clearance, the inner rotor will contact the outer rotor. In the analysis context, part of the computational domain will be lost, making the calculation impossible. Therefore, for accurate analysis, it is important to check all dimensions that affect the clearances as finely as the clearances themselves, such as whether the interaxis distance is accurately reflected in the model.

[3] Resolution of analysis model

The analysis model consists of connected triangular faces. The more complex the model, the more triangles are needed to represent the shape. Without taking this into account, for example, a smooth curved part of the model cannot be reproduced with these triangles, resulting in many angular parts. The model will not represent the clearances between the parts correctly, and in the worst case it may have problems such as disabled computation due to the inner and outer rotors touching each other.

Therefore, we refined the mesh to accurately reproduce the shape of the analysis model of the internal gear pump. Fig. 10 compares different mesh sizes of the curved part of the analysis model. In the finer mesh model, the curved part consists of more coordinate points to improve the resolution of the analysis model, which enables the accurate reproduction of the model.

2. 5 Results of CFD Analysis

In the following, the results of CFD analysis with/without consideration of the adjustment items mentioned in the previous section are compared with the experimental results (Fig. 11). Red dots indicate the analysis results without consideration and blue dots indicate the analysis results with consideration, while the black line shows the experimental results. According to the figure, the analysis before consideration shows a poor prediction accuracy, especially at one point (low speed) with a maximum of 22.5%, while the analysis after consideration shows a high prediction accuracy in all speed ranges, marking a maximum of 3.0%.

3 Design Proposal Case

3. 1 Internal Gear Pump Prototype

Assuming the cooling applications for eAxle drive units, the internal gear pump should use a low-viscosity hydraulic fluid from the viewpoint of cooling efficiency. The hydraulic fluids currently used in eAxle cooling pumps generally have a lower viscosity than the hydraulic fluid for the power steering and CVT, which are the development targets of KYB. Low viscosity hydraulic fluids are prone to turbulence at the same flow rate as thicker fluid. Turbulence can cause localized pressure drops, resulting in cavitation. Therefore, compared to conventional hydraulic pumps, eAxle cooling pumps raise concerns about lower volume efficiency due to the occurrence of cavitation. We then verified this issue with test results and found lower volume efficiency at high-speed ranges. Against this problem, we used CFD analysis and considered improvement suggestions to try to increase the efficiency. Fig. 12 shows the flow lines of the suction oil passage of the internal gear pump as viewed from the rotational axis, and Fig. 13 shows the amount of cavitation occurring in the pump chamber. These results showed that the oil could not be introduced up to the black circle point of the suction oil passage, resulting in many cavitation points inside the pump chamber. These could have reduced the volume efficiency. Therefore, we improved the shape of the suction oil passage to smoothly introduce the oil to the black circle point and suppress cavitation to improve volume efficiency.

3. 2 Improvement Strategies

Fig. 14 compares the shape of the suction oil passage as seen from a direction perpendicular to the axis of rotation before and after the improvement. The suction oil passage before the improvement had a sharp bend with a step just

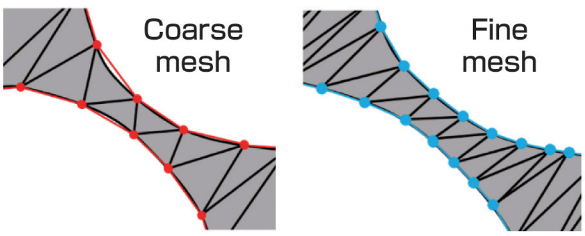

Fig. 10 Mesh comparison

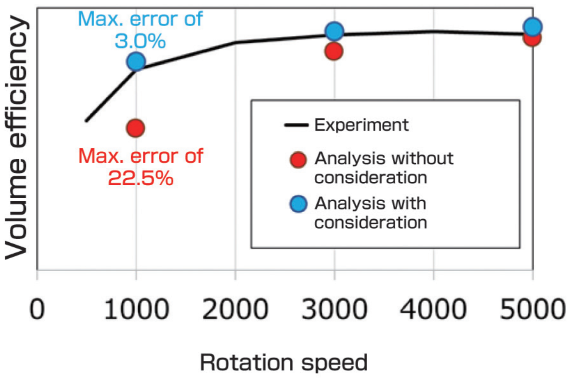

Fig. 11 Speed-volume efficiency

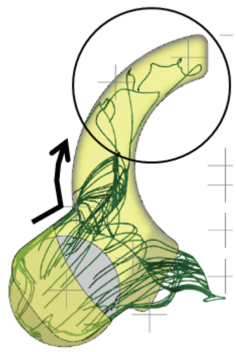

Fig. 12 Flow lines of suction oil passage before improvement

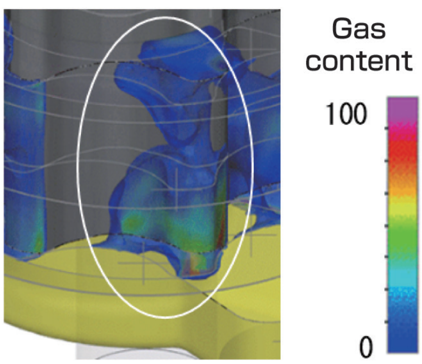

Fig. 13 Cavitation spots in the pump chamber

before entering the suction port. This step caused poor flow and prevented the oil from reaching the end of the suction port. After the improvement, the shape of the bend was modified to have a curvature and eliminate the step. In addition, the suction port was widened in the depth direction to allow the oil to flow to the end of the suction port.

Fig. 15 shows the shape of the suction oil passage as viewed from the direction of the rotational axis before and after the improvement. Compared with the bend before the improvement, the improved passage had no bend, so the oil can flow straight into the suction port.

3. 3 Results of Improvement

Figs. 16 and 17 show the results of the analysis of the flow lines of the suction oil passage after the improvement strategies were implemented, and the amount of cavitation occurring in the pump chamber, respectively. These results confirmed that the improved suction oil passage allowed the oil to flow smoothly into the end of the suction port and reduced the amount of cavitation in the pump chamber. The volume efficiency increased by a maximum of 2.6% at high speed.

After this analytical verification of the effect of the improved shape of the suction oil passage, we built and evaluated an actual prototype machine. Fig. 18 shows the results of a speed-volume efficiency test on the prototype pump under specified pressure and oil temperature conditions. The test showed that the volume efficiency at high speed increased by a maximum of 4.3% from the level before the improvement.

4 Concluding Remarks

This paper has generally explained the flow characteristic analysis technology for internal gear pumps, along with the analysis settings, the volume efficiency prediction accuracy, and a case study of the application of the analysis technology.

The flow characteristics of hydraulic pumps, especially their flow rate, can be reduced by three possible causes. Crevice leakage could be addressed by considering the clearances between parts in the analysis model. The other two phenomena (bubbles and cavitation) could be reduced by considering mixed flow and using a numerical model of cavitation to achieve high prediction accuracy for speed-volume efficiency.

This analysis technology was applied to an internal gear pump development project. We modified the shape of the oil passage of a prototype pump through an improvement activity to be able to suggest a design for higher volume efficiency.

From now on, we will work to construct a discharge pressure pulsation prediction technology that will contribute to the development of a high-efficiency, low-noise internal gear pump.

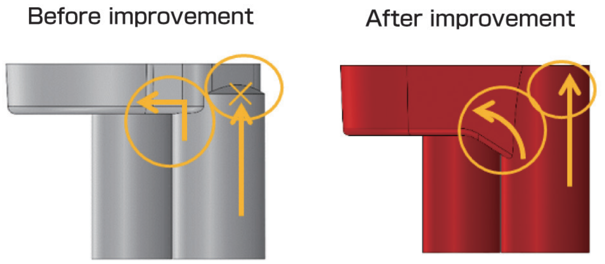

Fig. 14 Changing the shape of the suction oil passage

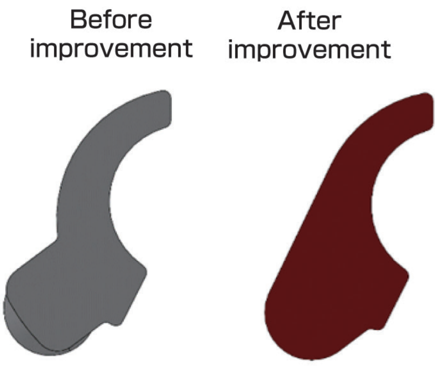

Fig. 15 Enlarging the suction oil passage

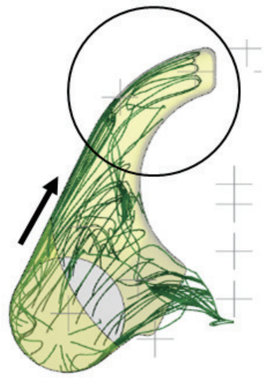

Fig. 16 Flow lines of suction oil passage after improvement

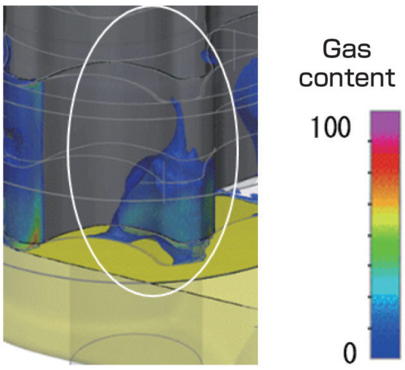

Fig. 17 Cavitation spots after improvement

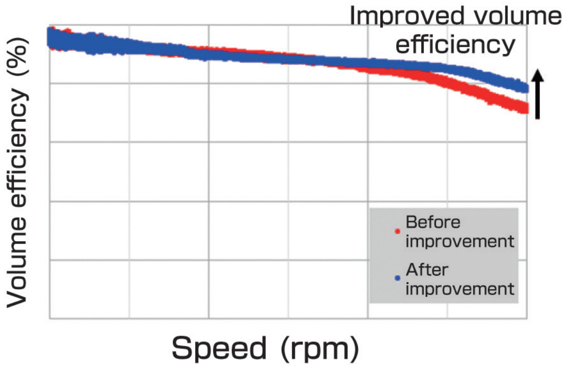

Fig. 18　Volume efficiency comparison result

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