The Latest Trends in Oil Pump Rotors for Automobiles

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Internal gear rotors are powder metallurgy parts widely used in automobile engine oil pumps, automatic transmissions (ATs), continuously variable transmissions (CVTs), and hybrid vehicle transmissions. In the 1980s, Parachoid rotors were developed and started to be used in automobile oil pumps to meet the growing needs for smaller and lighter oil pumps that achieve improved fuel efficiency. Recently, Megafloid, Geocloid, and Parachoid EX rotors have been developed to meet the needs for even smaller oil pump rotors to reduce friction loss. This paper introduces the development and evolution of these oil pump rotors.

Keywords: automobile, oil pump, internal gear, oil pump rotor, powder metallurgy

1. Introduction

Sintered internal gear pump rotors are widely used as key elements of automobile oil pumps. In typical applications, they lubricate engines, generate hydraulic pressure in automatic or continuously variable transmissions (AT/CVT) and feed fuel to diesel engines. Recent paradigm shifts in the automotive industry have spurred the use of sintered internal gear pump rotors in additional applications, such as lubrication of hybrid vehicle transmissions and electric motor-driven oil pumps.

To improve the efficiency of oil pumps, Sumitomo Electric Industries, Ltd. has developed and commercialized its proprietary tooth profiles such as Parachoid, Megafloid, and Geocloid rotors. Our latest product, Parachoid EX rotor, was developed and commercialized under the concept of achieving both high efficiency and low noise. We have also built a system designed to evaluate the performance and durability of discrete pumps. This was intended not only to verify the new tooth profile design, but also to reduce development time by conducting various tests of discrete oil pumps that have been conventionally performed by our customers.

This paper principally describes the development trends and examples of oil pump rotors that incorporate Sumitomo Electric's proprietary tooth profiles, from the Parachoid rotor to the most recently developed Parachoid EX rotor. The system designed to evaluate discrete oil pumps is also reported.

2. Development and Commercialization of High-Efficiency Pump Rotors

2-1 Internal gear oil pump mechanism

Figure 1 shows the structure of an oil pump that incorporates internal gear pump rotors. The inner and outer rotors are placed eccentrically within a case. The outer rotor has one more tooth than the inner rotor. The tooth tips of the outer and inner rotors form chambers. When the inner rotor is driven to rotate by means of a shaft inserted into the hole in it, the outer rotor, the outside of which is confined in the case, meshes with the inner rotor, receives torque, and rotates in the same direction. The volume of each chamber gradually increases with rotation, and after reaching its maximum, it gradually decreases. This process occurs repeatedly. As the chamber volume increases, the pump takes up oil via the suction port. When the chamber volume reaches maximum, the chamber is temporarily separated from both the suction and pressure ports. The pump discharges oil via the pressure port as the volume becomes smaller. This is the mechanism of oil pump operation.

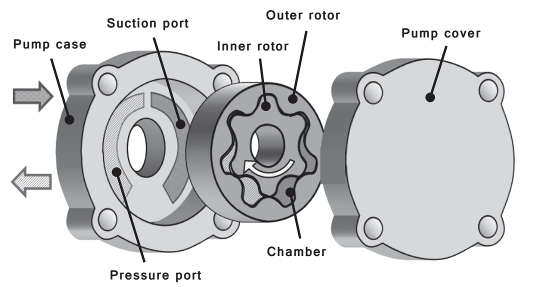


Fig. 1. Structure of oil pump incorporating internal gears

2-2 Development of Parachoid rotor incorporating our tooth profile

When the Parachoid rotor was developed, the tooth profiles used in oil pumps were mostly based on involutes.*1 The reasons for this were that involute tooth profiles were easy to work on in pump design due to advances in theoretical analysis achieved through many studies and were also easy to fabricate by tooth cutting. Oil pump rotors incorporating a trochoid,*2 on the other hand, had not yet been fully theoretically analyzed despite their many advantages.

We addressed this situation by conducting a theoretical analysis of trochoid-based tooth profiles and developing a tooth profile design system. The result showed successful commercialization of the Parachoid rotor. The Parachoid rotor has the Sumitomo Electric's proprietary tooth profile (registered utility model no. 06-039109) created by using a trochoid on the tooth profile of the inner rotor (Fig. 2) and the envelope of the inner rotor to form the outer rotor (Fig. 3). In comparison with the conventional trochoid-based oil pumps, the use of the envelope of the inner rotor to form the outer rotor reduced variation of tooth clearance during rotor rotation and reduced tooth clearance (Fig. 4). By reducing tooth clearance and improving sealing performance between the teeth, the Parachoid rotor achieves high efficiency (Volumetric efficiency = Actual discharge volume/Theoretical discharge displacement) even at high pressures required of oil pumps for ATs.

A crescent was required to be attached on the pump case (Fig. 5) for the internal gear pumps incorporating an involute tooth profile to ensure sufficient sealing performance between the teeth, particularly in high-pressure applications. Even in such internal gear pumps, the Parachoid rotor exhibited a comparable level of discharge performance to the involute tooth profile, demonstrating its potential for oil pump size and weight reduction. Consequently, its use expanded to AT oil pumps that must meet higher pressure requirements, as well as for engine lubrication applications.

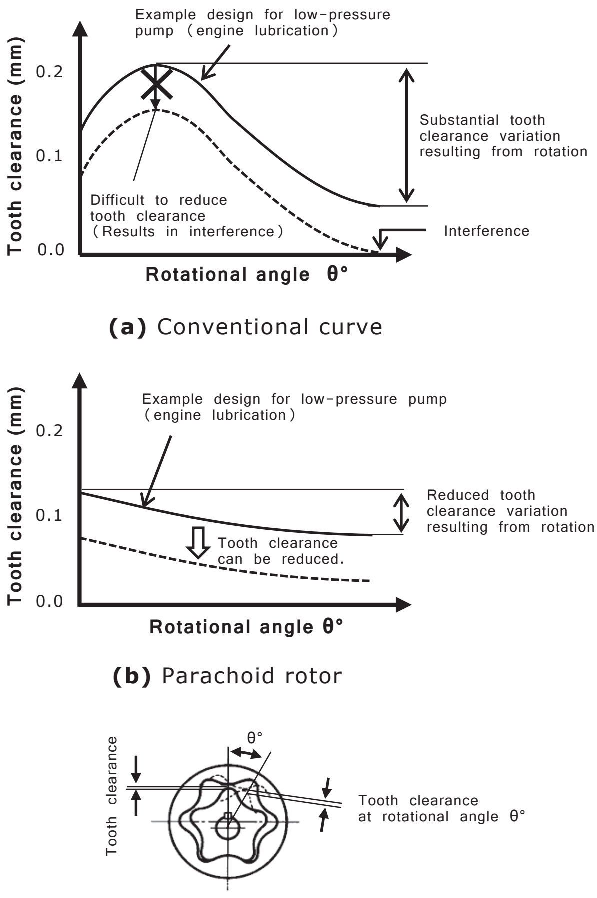


Fig. 4. Tooth clearance of Parachoid rotor

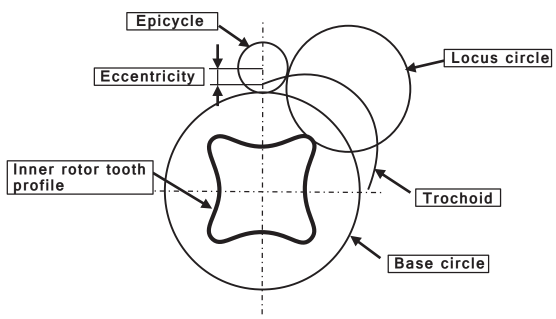


Fig. 2. Inner rotor tooth profile of Parachoid rotor

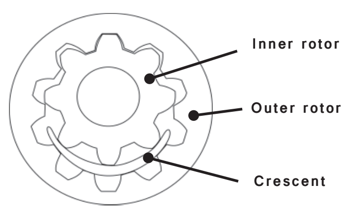


Fig. 5. Involute-based rotor

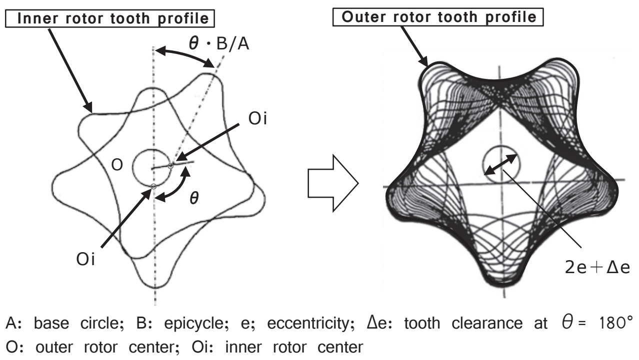


Fig. 3. Envelope curves used to form outer rotor (Registered utility model no. 06-039109)

2-3 Increase in pump efficiency

Demand for reduced energy loss in oil pumps has been growing each year for the sake of improving automobile fuel economy. Oil pumps account for a large part of energy loss in each unit that uses them. For example, energy loss attributable to the engine lubrication oil pump presumably accounts for 10% of total loss in the engine. That in oil pumps for ATs presumably accounts for 20% to 30% of total loss in the AT unit. To cut down energy loss in oil pumps, it is effective to reduce friction by downsizing the oil pump rotors. However, a smaller oil pump means a reduced discharge volume. For this reason, to reduce friction without compromising performance, it is necessary to develop new smaller oil pump rotors that achieve a comparable level of discharge volume to conventional rotors.

Oil pump efficiency is expressed as the product of volumetric efficiency and mechanical efficiency.

η_T (%) = η_v (%) x η_m (%) ÷ 100
η_v (%) = Q ÷ Q_{th} x 100
η_m (%) = (Q_{th} x P) ÷ (2πT) x 100

η_T: Pump efficiency (%)
η_V: Volumetric efficiency (%); η_m: Mechanical efficiency (%)
Q: Actual displacement; Q_{th}: Theoretical displacement
T: Drive torque; P: Discharge pressure

In these equations, the theoretical displacement is a fixed quantity dependent on the product of the maximum chamber volume produced by the inner and outer rotors and the number of inner rotor teeth. Important factors in improved pump efficiency are an increased actual displacement and reduced drive torque. Drive torque equals the sum of oil discharge and losses induced during rotor rotation by frictional resistance at each sliding portion. Reducing this sliding loss is one way to reduce drive torque.

Given the same theoretical displacement, drive torque decreases with decreasing outer rotor outside diameter, due to a decrease in the loss caused by frictional resistance (Fig. 6). In sum, reduction in rotor radial size is most effective for drive torque reduction.

Rotor diameter is chosen according to the inner rotor tooth profile, which is designed on the basis of pump specification requirements including displacement, driveshaft diameter, and number of teeth. Inner rotor diameter is designed according to the inside diameter (= driveshaft diameter), thickness [= (root diameter − inside diameter)/2] and tooth height [= (tip diameter − root diameter)/2]. The thickness is designed to ensure satisfactory part strength and sealing performance against oil leaks from the chamber to the driveshaft area, and tooth height is designed to meet the applicable displacement requirements. Theoretical discharge quantity per revolution is determined by the product of the maximum chamber volume and the number of inner rotor teeth.

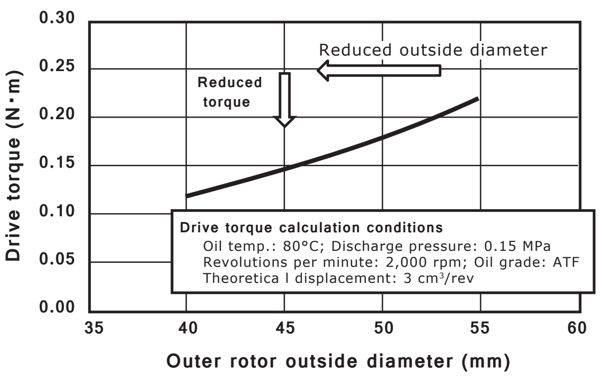


Fig. 6. Outer rotor outside diameter vs. drive torque

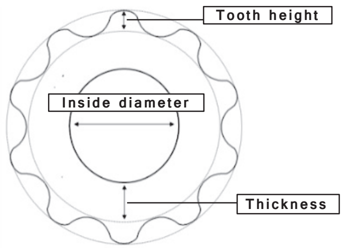


Fig. 7. Constituent factors of inner rotor

Accordingly, greater tooth height increases the maximum chamber volume and theoretical displacement.

The conventional design of inner rotor tooth profile based on a trochoid or cycloid is subject to design parameter limits. In such a design, therefore, it may be necessary to increase thickness (= sealing width) to meet the applicable pump specification requirements. In other words, the problem is a larger rotor size than required.

2-4 Development of Megafloid rotor

As described above, the conventional design of inner rotor tooth profiles based on a trochoid or cycloid[*3] (Fig. 8) results in a larger rotor size than necessary. The factor responsible for this is the tooth profile design method. Inner rotor tooth profiles are described by a point on an epicycle that is rolling without slipping along a base circle. The base circle diameter - and consequently, the rotor size - is uniquely chosen on the basis of the selected theoretical displacement and number of teeth. Consequently, to reduce the rotor size, it is necessary to enhance design flexibility for tooth profiles.

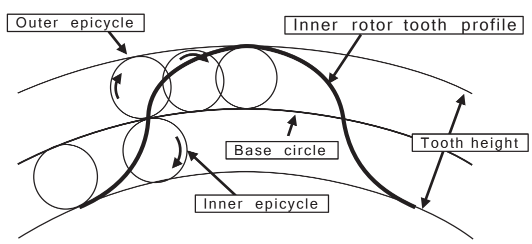


Fig. 8. Cycloid-based inner rotor tooth profile

As a solution to this challenge, the Megafloid rotor improved design flexibility for tooth profiles by incorporating an involute between cycloids drawn using two base circles (Fig. 9). This design method successfully reduced the rotor size by using a higher tooth than conventional ones and reducing the sealing width, which was wider than required in conventional tooth

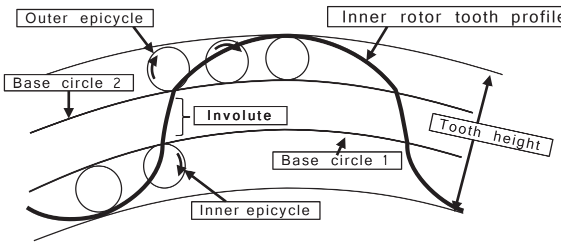


Fig. 9. Inner rotor tooth profile of Megafloid

profiles.

Sumitomo Electric's proprietary design method describes the outer rotor by a group of envelope curves of the inner rotor, as with the Parachoid rotor, so as to control the tooth clearance to a comparable level to the Parachoid rotor.

2-5 Development and commercialization of Geocloid rotor

Hybrid and electric vehicles, developed in line with the trends for improved fuel economy and environmental protection measures, spurred demand for reduced loss in oil pumps. Sumitomo Electric worked on the development of a tooth profile that would enable rotor downsizing, by augmenting design flexibility to surpass the Megafloid rotor.

The Geocloid rotor is the result of this attempt to achieve further improvement in design flexibility. Departing from the conventional tooth profile design technique, which creates tooth profiles on the basis of a base circle and epicycle, the new technique maneuvers the center position of a rolling generating circle in a desired manner and adopts the curve described by a point on the generating circle as a tooth profile curve (Fig. 10). With its higher-than-conventional design flexibility, the Geocloid rotor enabled small-diameter rotor design, reducing the sealing width to be smaller than the Megafloid rotor. In addition, it also enabled rotors of the same size as conventional ones to vary (= increase) in number of teeth. Moreover, Sumitomo Electric's proprietary design method, which describes the outer rotor by a group of envelope curves of the inner rotor, as with the Parachoid and Megafloid rotors, was adopted to optimize tooth clearance between inner and outer rotors and achieve high volumetric efficiency.

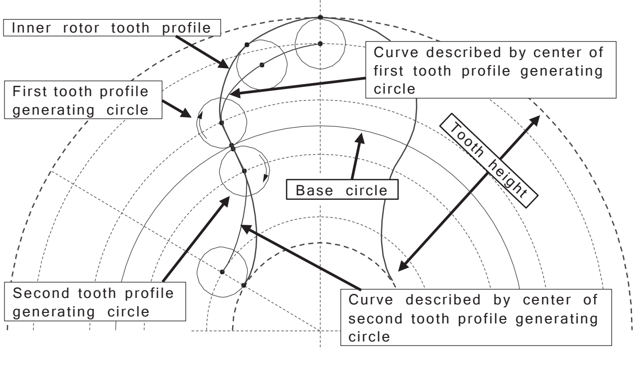


Fig. 10. Inner rotor tooth profile of Geocloid

2-6 Development of Parachoid EX rotor

In addition to growing demand for low-loss oil pumps, there is an increasing need for quiet oil pumps, in association with recently increasing electric motor-driven automotive parts. Sumitomo Electric has developed the Parachoid EX rotor to meet the need for a low-loss, i.e. small-diameter, yet quiet rotor.

Regarding quietness, Megafloid and Geocloid rotors, developed with the objective of reducing rotor diameter, perform less well than the trochoid-based Parachoid rotor, although depending to some extent on their application. One factor involved in this matter is increased backlash [maximum tooth clearance (Fig. 4)] between the outer rotor and inner rotor (Fig. 11). Megafloid and Geocloid rotors are based on involute or other non-epicycle curves in order to enhance tooth profile design flexibility. Hence, the amount of backlash tends to substantially increase with increasing tooth height. To reduce increases in the amount of backlash resulting from higher tooth height so as to achieve both downsizing and quietness, we addressed the challenge of improving tooth profile design flexibility by evolving the method used to design the trochoid-based Parachoid rotor.

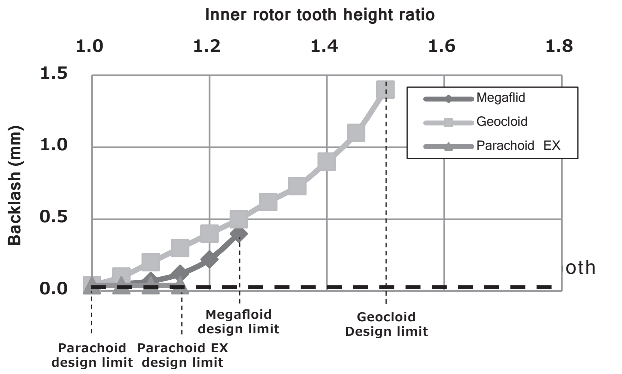


Fig. 11. Inner rotor tooth height ratios of different tooth profiles, with designable tooth height of Parachoid

One factor involved in the low design flexibility of the inner rotor of the Parachoid rotor is that the base circle, epicycle, and locus circle are almost uniquely chosen when pump specifications are established. With the conventional Parachoid rotor, the tooth profile is created in such a manner that an epicycle rolls without slipping along a base circle, a point that is apart from the center of the epicycle describes a trochoid, and a locus circle the center of which is on the trochoid gives envelope curves for the tooth profile. The Parachoid EX rotor is the same in this manner of creating a tooth profile. However, by using a larger-diameter locus circle at the roots than at tips of the inner rotor teeth, the

Parachoid EX rotor has increased tooth profile design flexibility (Fig. 12). This is an epicycle curve-based improvement in design flexibility. Hence, compared with Megafloid and Geocloid rotors, the Parachoid EX rotor tends to have less backlash resulting from increased tooth height. Consequently, the Parachoid EX rotor reduces the rotor diameter while retaining quietness.

Table 1 shows example designs of Parachoid, Megafloid, Geocloid, and Parachoid EX rotors.

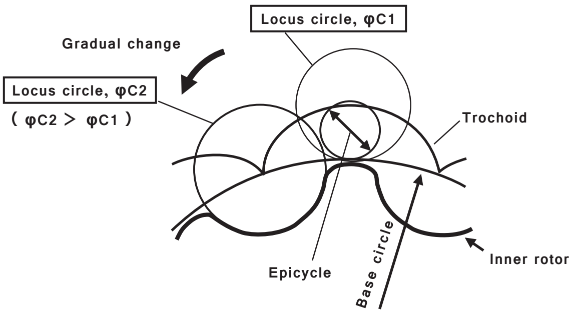
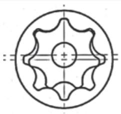
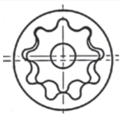
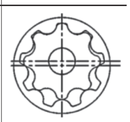


Fig. 12. Inner rotor tooth profile of Parachoid EX

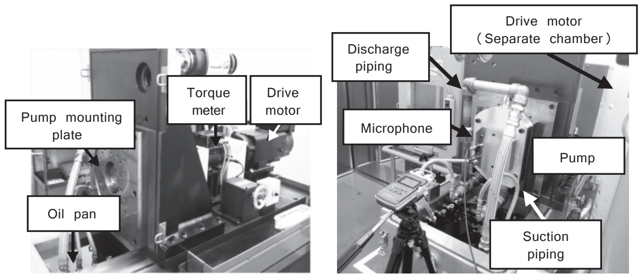
Table 1. Example tooth profile designs

Tooth profile	Parachoid	Megafloid	Geocloid	Parachoid EX
Rotor profile				
Outside diameter (Ratio)	ø54.6mm (100)	ø52mm (95)	ø48.6mm (89)	ø52mm (95)
Inner tooth height (_Ratio)	4.6mm (100)	4.8mm (105)	5.5mm (120)	4.8mm (105)
Theoretical displacement	3cm^3/rev			
Over all length	5.5mm			

3. Evaluation of Discrete Oil Pumps and Pump Performance

3-1 Oil pump evaluation equipment

Using its originally developed pump testing machines, Sumitomo Electric evaluates the basic performance, durability, and other oil pump properties to actively make development propositions regarding high-functionality parts. In line with recent trends towards electric motor-driven and downsized oil pumps, we have introduced testing machines capable of measuring low discharge volumes and torque accurately, as well as noise and vibration (NV) characteristics (Photo 1). In addition to the simple performance evaluation of discrete pumps, we, in collaboration with our customers, are able to meet needs for the development of constituent technologies for oil pumps, including the visualized evaluation of cavitation and pressure measurement in each pump section.



(a) Exterior of evaluation equipment (b) Example noise evaluation

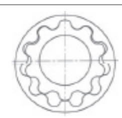
Photo 1. Evaluation equipment

3-2 Example development of Parachoid EX rotor

A comparative evaluation was conducted to ascertain the pumping performance of Megafloid and Parachoid rotors of the same size. Table 2 shows the evaluation specifications and conditions. The evaluation results are shown in Figs. 13 and 14 and Table 3.

This evaluation revealed that, like the Megafloid rotor, the Parachoid EX rotor is very quiet, while offering high volumetric efficiency and low drive torque.

Table 2. Evaluation specifications and conditions

Tooth profile		Megafloid	Parachoid EX
Rotor specifications	Number of teeth (inner/outer)	10/11	10/11
	Over all length	12mm	12mm
	Outside diameter	ø85mm	ø85mm
	Theoretical displacement	13.6cm^3/rev	13.6cm^3/rev
	Tooth profile		
Clearance specifications	Side clearance	Middle	Middle
	Body clearance	Middle	Middle
	Tip clearance	Middle	Middle
Test conditions	Oil type	ATF	
	Oil temp.	80°C : Drive torque (N·m) 120°C : Discharge volume Volumetric efficiency	
	Discharge pressure	1.0 MPa	
	Revolutions per minute	500 - 5,000 rpm	

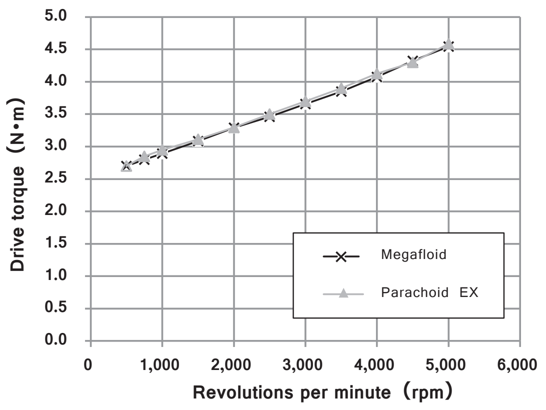


Fig. 13. Drive torque evaluation results

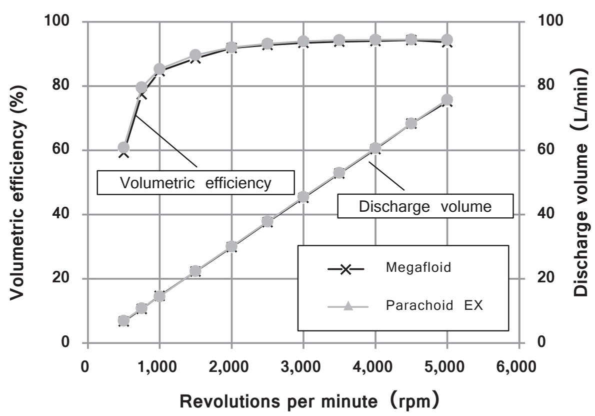


Fig. 14. Discharge volume/volumetric efficiency evaluation results

Table 3. Noise evaluation results (Unit: dB)

Revolutions per minute (rpm)	85°C × 0.5 MPa		80°C × 1.0 MPa	
	Megafloid	Parachoid EX	Megafloid	Parachoid EX
1,000	76	76	80	78
2,000	80	79	85	81

4. Conclusion

To meet the demand for automobile oil pumps, in particular for low-loss oil pumps, Sumitomo Electric has developed various tooth profiles beginning with the Parachoid rotor up to the latest Parachoid EX rotor. These tooth profiles have been used in diverse applications, including engine lubrication and hydraulic pressure generation in transmissions (AT/CVT). Presently, they are also used to lubricate hybrid vehicle transmissions and in electric motor-driven oil pumps. Expectations are high for deployment of these tooth profiles in innovative future mechanisms.

Fuel economy regulations and demand for environmental protection measures are expected to be additionally strict. To meet this challenge, we will work on the development of next-generation tooth profiles for more fuel-efficient and quieter automobiles as well as for other applications.

Technical Terms

*1 Involute: The curve described by one end of a taut string wound around a cylinder when the string is unwound.

*2 Trochoid: The curve described by a fixed point on a circle when the circle rolls without slipping along a curve.

*3 Cycloid: The curve described by a fixed point on the rim of a circle when the circle rolls without slipping along a curve.

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