

Development of a Magnetic Coupling Type Water Pump for 4-Stroke 50 cm³ Scooter Engines

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ABSTRACT

In the development of a magnetic coupling type water pump, the coupling pull-out phenomena, which leads to the impeller stopping, has been a concern. As a result of analysis of magnetic coupling behavior, two-types of pull-out were determined: pull-out due to insufficient transmission torque of the magnetic coupling in the high speed rotation range; and, pull-out due to the resonance of the inner and outer magnets. Major factors causing pull-out are the angular velocity input to the drive side, the inertia moment of the driven side, magnetic coupling characteristics, and the damping effect of coolant. Using the results of actual testing and a behavior simulation of a water pump, design specifications for a magnetic coupling were set within conditions that did not allow pull-out to occur. Consequently, the reliability of drive power transmission was assured. As a result, it was possible to decrease the size and weight of the water pump, and, at the same time, decrease engine friction.

1. Introduction

Water pumps in conventional internal combustion engines drive the impeller by a mechanical coupling, and thus it is necessary to have, on the drive shaft, a mechanical seal, an oil seal, and a shaft bearing. In comparison, with a magnetic coupling type water pump, the drive force is transmitted magnetically, and so the above-mentioned parts can be eliminated. This simplifies the structure, making it smaller and lighter, and also reduces engine friction.

The drawbacks of a magnetic coupling type pump are that due to sudden changes in rotational speed or at high rotational speeds, the driven side (impeller side) cannot

follow the drive side, creating a pull-out phenomena (referred to as pull-out hereafter). When pull-out occurs, the impeller stops, and because the coolant ceases to circulate, there is a problem with engine cooling.

With a magnetic coupling type water pump, generally, in contrast with an electric motor driven pump, a shaft connected to the internal combustion engine's crankshaft drives the pump. Accordingly, it is used from low rotational speeds to high rotational speeds and there is large rotational speed fluctuation during a single revolution. These are severe conditions of use for the magnetic coupling, and it has been a big concern in guarantying the reliability of drive force transmission.

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This project has analyzed the pull-out mechanism, verified the effects of each factor, and established the appropriate specifications. This technology has been adopted for the 4-stroke 50 cm³ scooter engine.

2. Structure

Fig. 1 shows the structural diagram of the magnetic coupling type water pump developed in this project. The special features are listed below.

- Because the water pump's impeller drive is carried out by the magnetic force of magnets, via a plastic pump case that separates water and oil, mechanical seals and oil seals are unnecessary.
- The impeller bearing structure eliminates the ball bearing, by using a slide bearing structure, of the type where the stainless steel shaft and the plastic bushing have direct contact.
- As for the magnets, as countermeasures to them breaking or to prevent them from flying off, the magnet on the camshaft side (the drive side, referred to hereafter as the outer magnet) is covered by a thin stainless steel wall, and the magnet on the impeller side (driven side, referred to hereafter as the inner magnet) is covered by plastic which integrates it into the impeller.
- As the camshaft drive, the outer magnet is fastened together with the cam sprocket.
- As the structure's water path is completely watertight, the seal performance is highly reliable, and the drain outlet structure, which conventionally was indispensable, is not necessary.

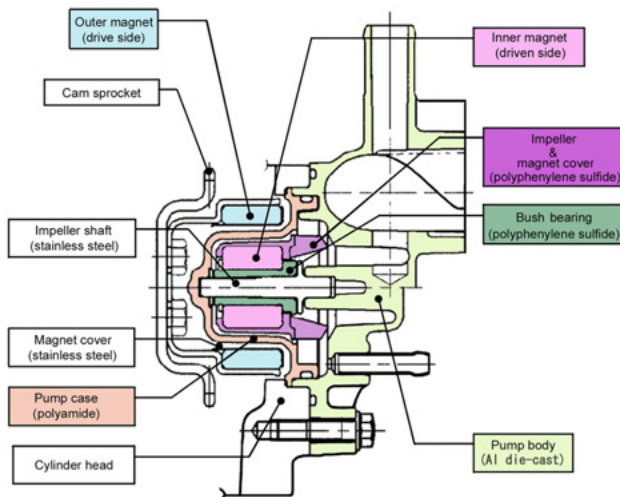


Fig. 1 Structure of magnetic coupling water pump

3. Pull-out Mechanism and Factors

In order to verify the pull-out phenomena, the behavior of the magnetic coupling's inner magnet and outer magnet were confirmed. The results of the behavior check showed that there are two types of pull-out: pull-out that occurs in high rotational speed range, and pull-out due to resonance of the inner magnet and outer magnet.

The pull-out in the high rotational speed range occurs because the water pump rotational torque exceeds the magnetic coupling's transmission torque.

The pull-out occurs due to resonance between the outer magnet's rotational speed fluctuation caused by fluctuation in engine speed and the inner magnet's rotational speed fluctuation caused by drive force transmitted by magnetic force. Due to the resonance, there is a large relative angle difference of the magnetic poles of the inner and outer magnets (referred to hereafter as phase difference), and if it exceeds the maximum pole phase difference where drive force transmission is possible, pull-out occurs.

The impeller behavior equation of motion is shown below⁽¹⁾.

$$I\ddot{\theta}_{in} + C\dot{\theta}_{in} - k(\theta_{in} - \theta_{out}) = 0 \quad (1)$$

- I : Inner magnet inertia moment
 C : Damping force of coolant
 k : Magnetic coupling's torsion spring effect
 θ_{in} : Inner magnet displacement
 θ_{out} : Outer magnet displacement

Based on the equation of motion, factors thought to affect pull-out were studied. Those factors are shown in Fig. 2. Among the factors that affect pull-out, one having a large effect is the magnetic coupling transmission torque characteristics, which is the core of this mechanism.

Magnetic coupling transmission torque changes according to the following:

- magnetic force
- temperature
- gap between magnets (radial direction, thrust direction)
- phase difference
- number of poles

As for the magnetic force, the higher the magnetic flux density of the magnetic body used, the larger the transmission torque. However, in this new development, attention was focused on stable ferrite to inexpensively deal with reduced magnetism. Also, the larger the magnet's dimensions, the larger the transmission torque. However, the inertial moment also increases with magnet size. The magnet's dimensions, within the actual engine layout, were established for the minimum inertia moment for the required transmission torque.

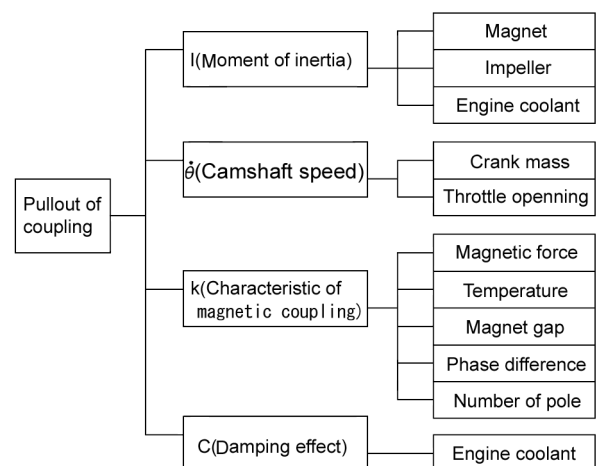


Fig. 2 Magnetic coupling pullout factor analysis chart

The relationship between transmission torque and temperature is shown in Fig. 3. With the ferrite magnet, the temperature coefficient of the magnetic force is large, and the characteristics are such that with a temperature rise, the magnetic force drops reversibly. When used in an internal combustion engine, the temperature range of use is broad, and so magnetic force changes due to temperature conditions have a large effect on transmission torque. The tests results show that the following equation is true.

$$T(t') = T(t) \cdot e^{k(t'-t)} \quad (2)$$

$T(t)$: Static maximum transmission torque (measured when temperature is $t^{\circ}\text{C}$)

$T(t')$: Static maximum transmission torque when temperature is $t'^{\circ}\text{C}$

k : reversible temperature coefficient

If the gap between the magnets increases, magnetic flux density drops, and so transmission torque drops. Transmission torque also drops due to misalignment of the thrust direction of the outer and inner magnets.

In magnetic coupling, drive force is transmitted by restoration force generated when phase difference between opposing magnetic poles is applied. This restoration force is from the attraction and repulsion acting between opposing poles and poles adjacent to them, and so changes according

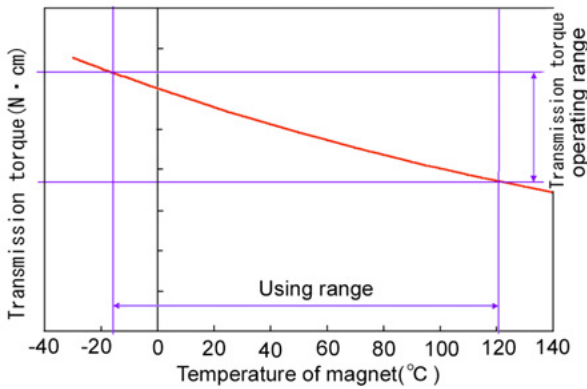


Fig. 3 Relationship between transmission torque and temperature of magnet

to their positional relationship⁽²⁾. Fig. 4 shows the relationship between phase difference according to differences in number of poles and transmission torque. The phase difference and transmission torque characteristics occur under conditions when gap magnetic flux density distribution is a sine wave, and strictly speaking a 3D analysis is required. However, from the test results in this development project, the relationship approximates the following equation.

$$T = T_{\max} \cdot \sin\{(P/2) \cdot \theta\} \quad (3)$$

T : Static transmission torque when the phase difference is θ

$T_{\max}$: Maximum static transmission torque

P : Number of magnetic poles

θ : Phase difference

As shown in Fig. 4, the smaller the number of poles, the larger the angle range wherein torque transmission is possible (permissible phase difference until pull-out).

However, as the maximum transmission torque changes according to the number of poles, it is necessary to study the optimum number of poles, while considering both transmission torque and angle range wherein torque transmission is possible.

4. Pull-out in the High Revolution Speed Range

Using a magnetic coupling with low transmission torque settings, confirmation tests were implemented of pull-out due to water pump unit motoring. Fig. 5 shows the water pump revolution torque characteristics used in the tests. The revolution speed when pull-out occurred was the point where the transmission torque of the magnetic coupling used in the test was the same as the pump revolution torque (see "a" in Fig. 5). The same results were also obtained in actual engine confirmation testing. From the above it was learned that, high revolution range pull-out occurs when pump revolution torque exceeds magnetic coupling transmission torque. Therefore, it is possible to avoid high revolution range pull-out by establishing pump revolution torque and magnetic coupling transmission torque while considering actual engine use conditions.

5. Resonance Pull-out

First, inner magnet and outer magnet revolution speeds were measured. Next, the inner magnet and outer magnet speed difference was integrated, and relative behavior was determined as the mutual angle difference from the position at the start of the measurement. As an example of measurement results, the left side of Fig. 6 shows the inner

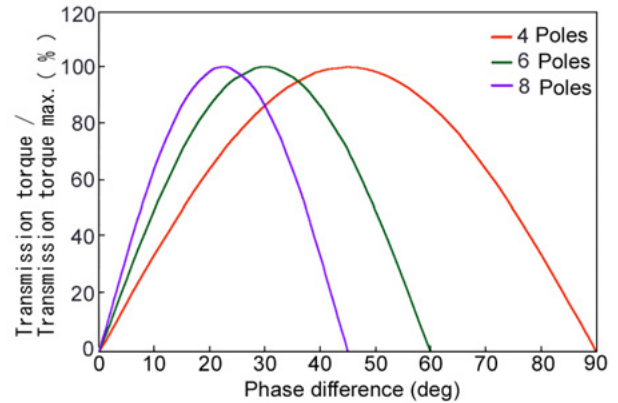


Fig. 4 Relationship between transmission torque and phase difference

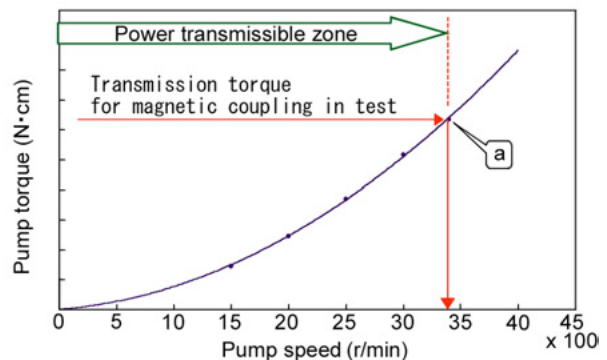


Fig. 5 Pullout point at high revolution speeds

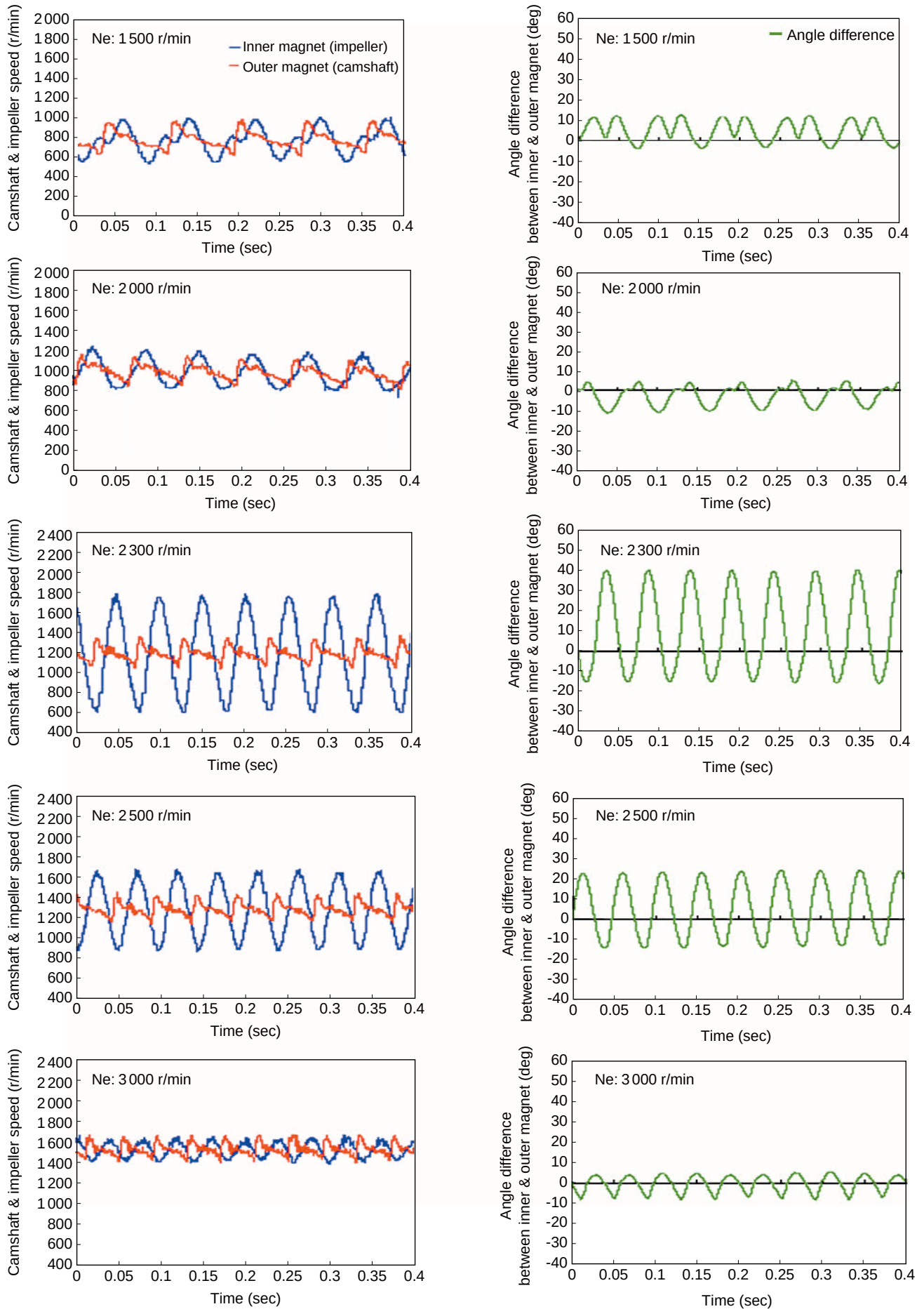


Fig. 6 Magnetic coupling behavior

magnet and outer magnet revolution speeds, and the right side of Fig. 6 shows the relative angle difference which is the result of integrated calculation. The total amplitude of the relative angle difference determined here is called the amplitude of phase difference. Next, the maximum amplitude of phase difference at each engine revolution speed was obtained, and was shown as the relationship between engine revolution speed and amplitude of phase difference. The data in Fig. 6, shown as the relationship between engine revolution speed and amplitude of phase difference, is Fig. 7's inertia moment 2.61×10^{-6} (kg·m²) specification. The smaller this amplitude of phase difference, the greater the tolerance against pull-out. Also, when the amplitude of phase difference increases, if it exceeds the pole's maximum phase difference at which drive force transmission is possible, pull-out occurs. In this way, the effect of each factor on pull-out was compared.

5.1 The Effect of Inertia Moment

A comparison was made of three specifications wherein inertia moment was changed on the inner magnet side by using a dummy weight, without changing the magnet unit. The amplitude of phase difference for each engine speed was determined; the results are shown in Fig. 7. The greater the inertia moment, the greater the tendency for resonance revolution speed range to be in a low revolution range, and the results showed that the amplitude of phase difference also grew. The smaller the inertia moment, the greater the tolerance against pull-out.

5.2 The Effect of Angular Velocity Input on the Magnetic Coupling

The effects of angular velocity input on coupling according to differences in throttle opening were verified. Fig. 8 shows the engine speed fluctuation according to throttle opening differences and the amplitude of phase difference characteristics. As the throttle opening becomes larger, the amplitude of phase difference also grows; at a throttle opening of 40%, it is basically saturated. This trend corresponds to that of the engine speed fluctuation. Magnetic coupling behavior results show that the greater the engine speed fluctuation, the more the tendency for the resonance revolution range to be to the low revolution side. The amplitude of phase difference also increases towards the low revolution side. In addition, as shown in Fig. 9, the results when engine speed fluctuation is varied according to flywheel mass are the same as results when varied according to throttle opening differences. Concerning magnetic coupling input, the smaller the fluctuation of angular velocity, the better tolerance against pull-out.

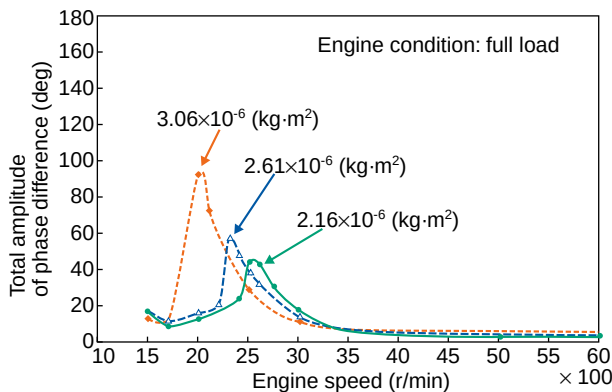


Fig. 7 Influence of inertial moment

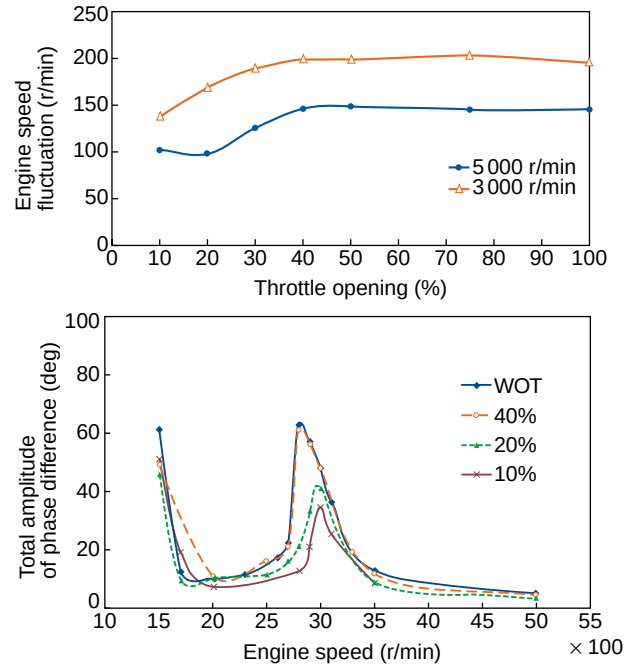


Fig. 8 Influence of throttle opening

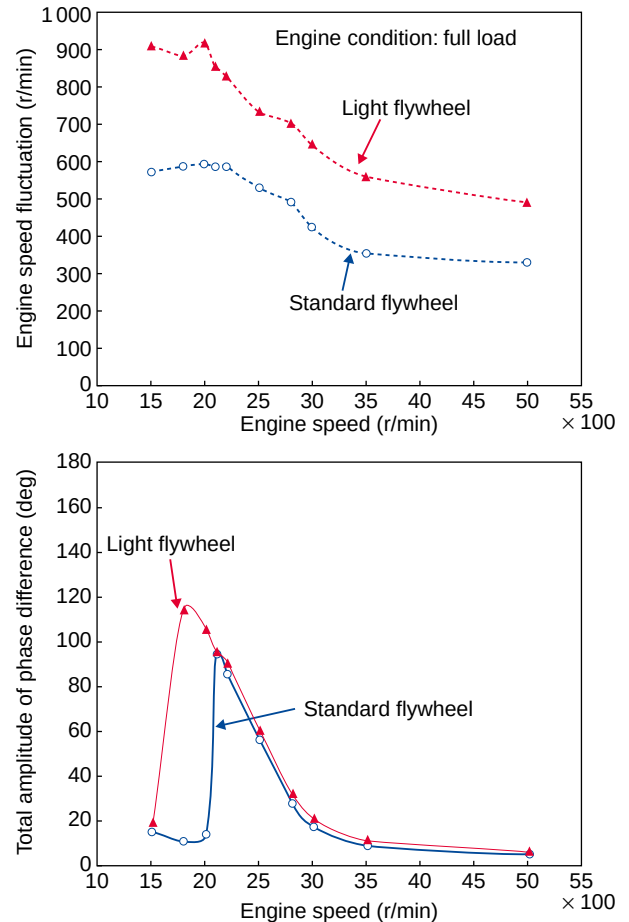


Fig. 9 Influence of flywheel inertial mass

5.3 The Effect of the Magnetic Coupling Characteristics

First, confirmation was made of the effects on pull-out of magnetic coupling magnetic force, temperature, and gap differences. As explained above, each of these factors affects transmission torque. The specifications used in the actual engine confirmation testing are given in Table 1. In addition, Fig. 10 shows the temperature characteristics for those specifications. Fig. 11 shows the results of confirmation of amplitude of phase differences at points A through D in Fig. 10. Measurement results at points A, B, and C show a resonance range whereby the smaller the transmission torque the larger the amplitude of phase difference on the low revolution speed side. As the transmission torque increases, the resonance range moves to the high revolution speed side, and amplitude becomes comparatively small.

Table 1 Magnet coupling specification for experiment

No.	1	2	3
Number of magnet poles	4	4	4
Driven magnet outer dia. (mm)	24	24	24
Drive magnet inner dia. (mm)	35	36	37
Gap (mm)	5.5	6	6.5

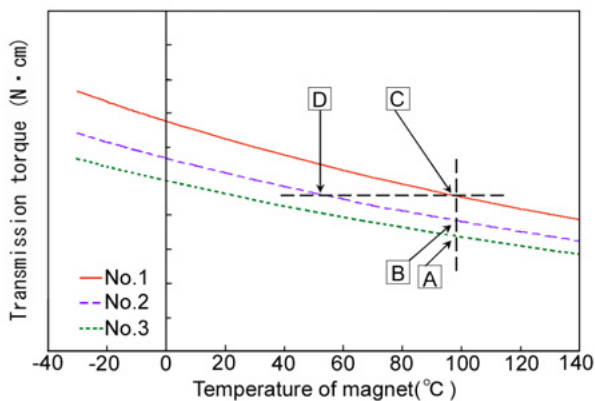


Fig. 10 Relationship between transmission torque and temperature for experiment

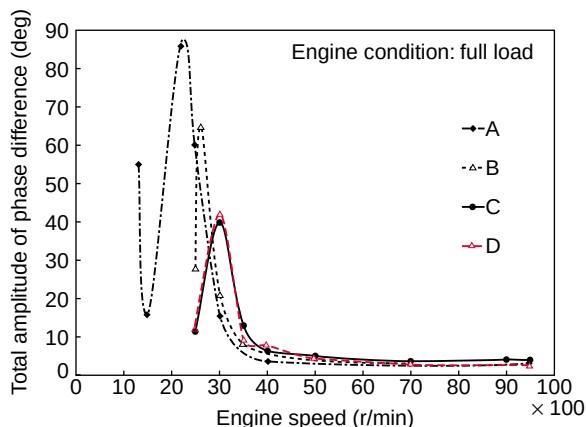


Fig. 11 Influence of magnet gap and temperature

Also, as a result of confirming that transmission torque is the same at points C and D, it was found that the characteristics where resonance occurs are also the same. From the above, it is known that it is possible to convert the factors of magnetic force, temperature, and gap with a transmission torque index.

The results of the next measurement of the effect of the number of poles are shown in Fig. 12. In order to eliminate the effects of a different maximum magnetic transmission torque due to a different number of magnetic poles, confirmations were carried out after adjusting transmission torque to be the same, using temperature settings. In comparison with the 6-pole spec, the 4-pole spec shows a large tolerance to pull-out angle and a resonance range on the low revolution speed side, even though the amplitude of phase difference is large. In addition, when there is a first order resonance range in the high revolution speed range around 4000 rpm and higher, it was found that there is a half order resonance range in the practical revolution speed range around 2000 rpm and higher.

5.4 The Effect of Coolant

First, assuming opening and closing of the thermostat, the effects of the amount of coolant flow were confirmed. The amplitude of phase difference was determined at a fixed revolution speed with varied flow. The measurement results are shown in Fig. 13. It was learned that differences in flow had no significant effect on amplitude of phase difference or resonance revolution range. Next, the effect of viscosity changes, due to coolant concentration,

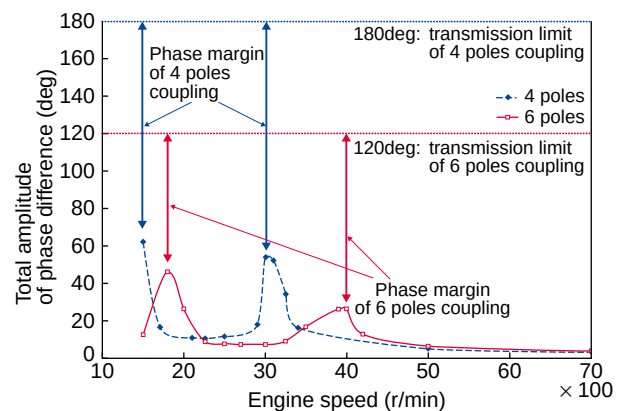


Fig. 12 Influence of number of magnet poles

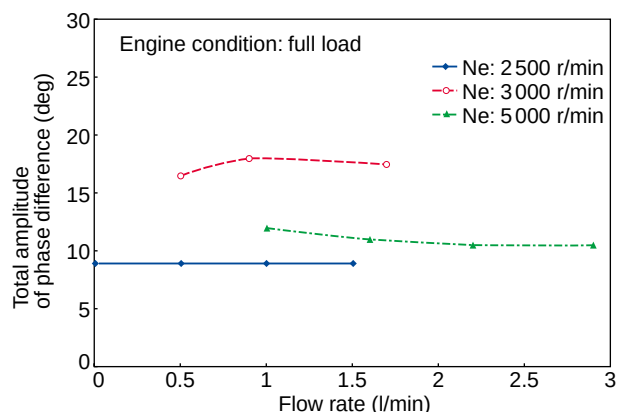


Fig. 13 Influence of flow rate

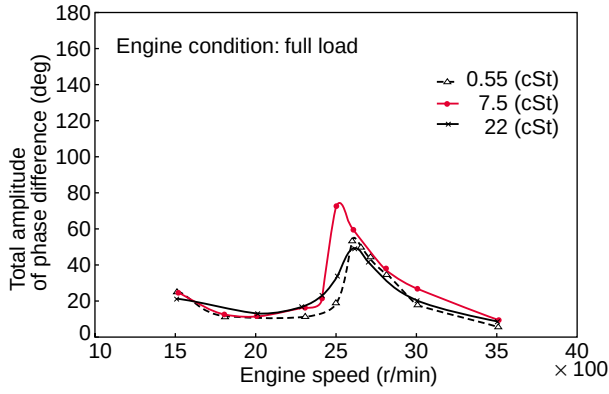


Fig. 14 Influence of viscosity

temperature, etc., was confirmed. The measurement results are given in Fig. 14. It was learned that viscosity differences had no significant effect on amplitude of phase difference and resonance revolution range.

6. Simulation

In order to learn the appropriateness of the resonance pull-out mechanism, a simulation was implemented. Fig. 15 shows the simulation model. A special feature of this system is that the equation of motion is non-linear, because magnetic force load acting between the inner magnet and outer magnet, that is to say the transmission torque, is not linear against displacement. The analysis method of this system uses the Newton-Raphson method of numerical integration. In comparison with the inner magnet side, the outer magnet side has sufficiently large mass, and so it was not modeled. Rather, the angular displacement of the outer magnet at each time obtained from the actual measurements was input into the calculation model. The calculation equation used in the simulation is shown below.

$$I\ddot{\theta}_{in} + C\dot{\theta}_{in} - k(\theta_{in} - \theta_{out}) = 0 \quad (4)$$

I : Inertia moment on the inner magnet side

C : Resistance due to the coolant (pump revolution torque)

$$k(\theta_{in} - \theta_{out}) = T_{max} \cdot \sin\{P/2(\theta_{in} - \theta_{out})\} \quad (5)$$

$k(\theta_{in} - \theta_{out})$: Static transmission torque when the phase difference is θ

T_{max} : Maximum static transmission torque

P : Number of magnetic poles

θ_{in} : Inner magnet displacement

θ_{out} : Outer magnet displacement

$$\theta_{out} = \int \omega(t) dt \quad (6)$$

$\omega(t)$: Outer magnet angular velocity

Fig. 16 shows the actual measurement and simulation results of inner magnet angular velocity when the engine running condition is a sweeping engine speed. There is close agreement between the two sets of results, and thus the appropriateness of this system's equation of motion was confirmed. Further, theoretical evidence of the pull-out phenomena occurring in engines was obtained.

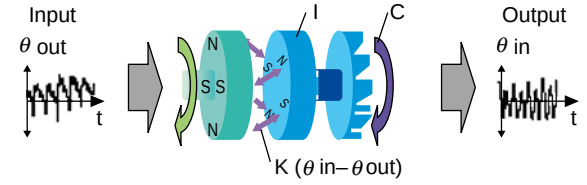


Fig. 15 Simulation model

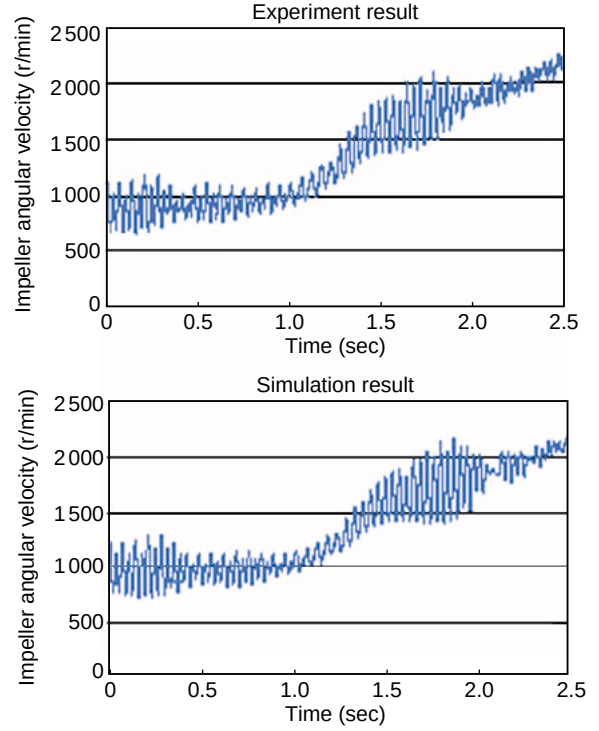


Fig. 16 Comparison between simulation and experiment results

7. Specification Settings and Benefits

In establishing specifications, the magnet temperature, angular velocity input to magnet coupling, and pump revolution torque are measured for the vehicle to which the system will be applied. A simulation is carried out whereby four specifications are varied to confirm the system. The four specification items are: number of magnetic poles, transmission torque, inertia moment, and angular velocity input. Fig. 17 provides an example of the results of simulation of a 4-pole spec, with fixed input, for the transmission torque and different inertia moments. Each specification was simulated and the results are provided in this graph, which shows the pull-out margin angle as an index. Specifications were selected based on the results of these simulations. Then, after confirmation testing with an actual engine, drive force transmission reliability under various conditions of use was guaranteed. By adopting this magnetic coupling water pump, pump unit friction was reduced to 1/5 (when $N_p = 4500$ rpm) compared with conventional mechanical coupling water pumps. Further, the new pump is smaller and lighter, and the structure has been simplified.

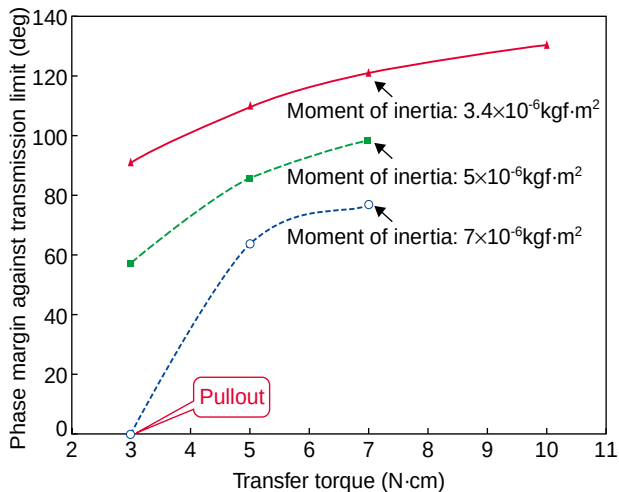


Fig. 17 Simulation results for transmission torque and inertia

8. Summary

In developing a magnetic coupling water pump for use in a 4 stroke 50 cm³ scooter engine, the focus was on angular velocity input to drive side, driven side inertia moment, magnetic coupling characteristics, and coolant damping effect. The results of a behavior simulation for each factor and vehicle confirmation tests showed the following achievements.

- (1) The pull-out mechanism has been clarified.
- (2) Theoretical specification investigations are now possible due to this water pump behavior simulation program.
- (3) Drive force transmission reliability is guaranteed using vehicle confirmation tests and simulations.
- (4) Engine friction reduction, smaller and lighter pumps, and a simplified structure have been achieved.

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