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Small Size Hydraulic Pumps with Low Heat Generation for Electro Hydrostatic Actuation of Humanoid Robots*

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***Abstract*— In this research, we suggest a method to reduce the loss of the pump aiming to develop small and high-pressure pump for EHA. To reduce the loss of the pump, we focused on the internal leakage loss and the viscous friction loss. We formulated each loss and found that it is effective for loss reduction to make gaps inside the pump narrower and increase the discharge amount per 1 rad making the radius of the gear small. Based on the above, we developed the improved involute external gear pump. Compared with conventional trochoid pump, the internal leakage loss of developed pump is reduced by 22.4% at 10MPa and the viscous friction loss is reduced by 85.6% at 10MPa. Also, there is a problem that internal leakage increases when the internal pressure becomes high. This problem is caused by the deformation of the pump-casing under high pressure. We developed highly rigid ceramics-casing to reduce the increase of the internal leakage. Compared with the pump using aluminum-casing, the pump using ceramics-casing reduced 56.2% in internal leakage loss when the internal pressure increased from 3MPa to 6MPa.**

I. INTRODUCTION

Robots which perform cooperative work with people or rescue activities at a disaster area require shock-resistance and overload protection. So, actuators of those robots need to be shock-resistive. Many robots adopt gear reducer such as harmonic drives as an actuator because of their accurate positioning. However, they lack shock-resistance and back-drivability, the ability to reverse transmission from the output to the input.

As a shock-resistive actuator, Series Elastic Actuators (SEA)[1] has been developed. SEA incorporates an elastic element at the output end, so it has shock-resistance and high back-drivability. SEA modules[2] and robots[3][4] equipped with SEA have been developed. However, there is a problem that SEA is difficult to control due to the vibration caused by the elastic element. A hydraulic actuator is also a shock-resistive actuator because it receives a force by a surface. For example, BigDog[5] is the tough quadruped robot which uses hydraulic actuator. The hydraulic actuator also has an advantage that it is easy to install the safety mechanism. A typical hydraulic actuator uses servo valves to control flow rate and pressure. A problem of the hydraulic system using servo valves is that it loses back-drivability when the valve is closed. On the other hand, Electro-Hydrostatic Actuator (EHA)[6][7][8][9] has shock-resistance and high back-drivability. EHA controls the flow rate and pressure by controlling the electric motor. It has high back-drivability because it don't need valves. Also, EHA has an advantage of low heat generation because there is no friction loss at the valves. However, it is difficult for EHA to generate instantaneous power. There is a problem that the system using EHA tends to be large because at least one pump is required for one actuator. The volume and weight of pumps occupy a large proportion of the robot driven by EHA. While pumps of robots need to output high pressure, the size and the weight of the pump of EHA need to be small. There is a case that miniaturized pump of EHA for aerospace applications has been developed[10].

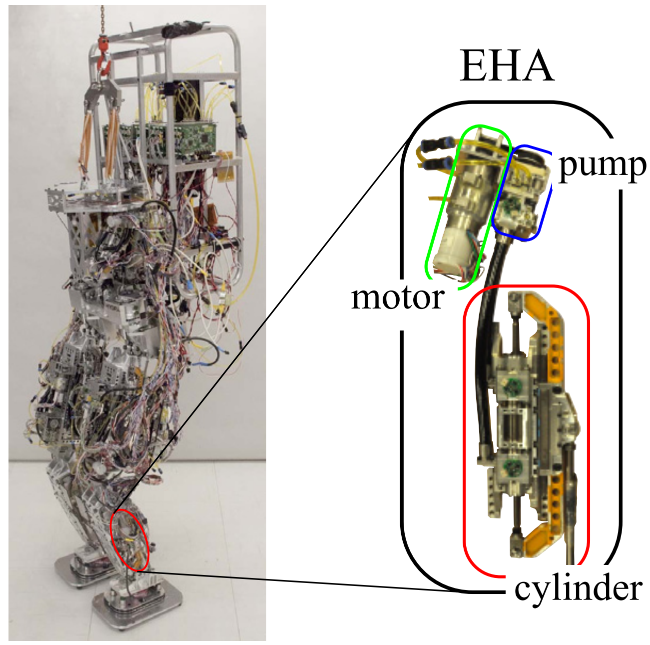

Fig. 1. Linear EHA Mounted on each Joint of Humanoid Robot Hydra

In this research, we suggest a method to reduce the loss of small and high-pressure pump for EHA on humanoid robots.

II. OVERVIEW OF DEVELOPED PUMP FOR EHA

A compact and high power EHA for humanoid robot Hydra[11] has been developed as shown in Fig.1. As the pump for EHA, a trochoid pump is adopted because of its low friction. The small trochoid pump developed by Kaminaga et al.[8] has a structure as shown in Fig.2. In this pump, there are mainly three places to adjust the number of

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shim rings of 10μm thickness so that the gap width between gear and casing can be adjusted. The distance between the casing X and the gear of the drive shaft can be adjusted by shim rings I, the distance between the casing X and the driven gear can be adjusted by shim rings II, and the distance between the casing Z and the respective gears can be adjusted by shim rings III.

Aluminum alloy is mainly used for the pump-casing to save weight. The weight and size of this trochoid pump are shown in Table.I. The maximum discharge pressure of this pump is 5.6MPa.

III. LOSS OF THE PUMP FOR EHA

Heat generated from the loss is the main cause of the performance degradation of the pump. When heat is generated, the temperature of hydraulic fluid rises which causes the reduction of the viscosity of the oil. As the viscosity becomes low, the internal leakage increases. Therefore, it is necessary to reduce the loss of the pump. Loss of the pump can be classified as below.

1) Internal leakage loss
2) Viscous friction loss
3) Coulomb friction loss

Internal leakage is a phenomenon that oil leaks from high-pressure side to low-pressure side inside a hydraulic equipment when a differential pressure is generated. As shown in Fig.2, there are two types of the sources where the internal leakage occurs in the pump: one is the gap ① between the gear and the casing, the other is the gap ② at the tooth tip of the gear. We assumed that the internal leakage amount at the gap ② is small enough compared to the one at gap ①. This is because there is a line contact at the gap ② while there is almost no contact at the gap ①.

Viscous friction is the friction caused to an object moving in a fluid. This friction is proportional to the rotational speed. Coulomb friction doesn't depend on the rotational speed. Internal leakage and friction cause not only heat generation but also the reduction in the robustness and position tracking accuracy[12].

IV. EXPERIMENT TO INVESTIGATE THE ENERGY LOSS OF CONVENTIONAL EHA

We conducted the experiment to investigate the distribution of energy loss of EHA. In this experiment, we made linear EHA reciprocating motion at a constant speed using a powder brake as a load device as shown in Fig.3. The linear EHA consists from a trochoid pump and double rod cylinder. The electric motor transmits torque to the input shaft of the pump via pulleys and a timing belt. The speed of the cylinder was 15 mm/s and the loads given by the powder brake were about 100, 140, 270, 580, 880, 1200N. We used a linear encoder for acquiring the piston position and speed, an encoder for acquiring the rotational speed of a motor, pressure sensors for acquiring the pressure of the pump, a current sensor for acquiring the input current to the motor.

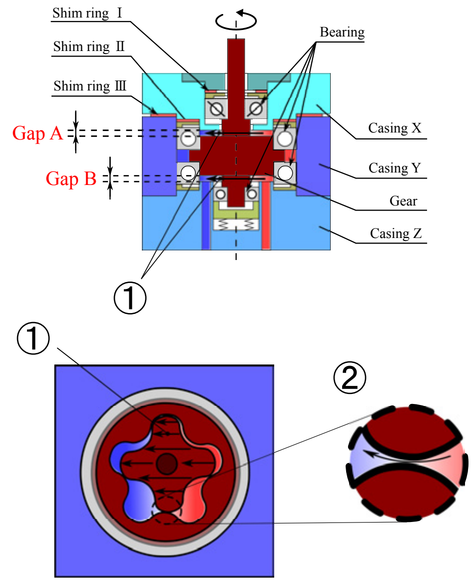

Fig. 2. The Place where Internal Leakage Occurs in the Pump (①: the gap A and B between the gear and the casing X (or Z), ②: the tooth tip of the gear.)

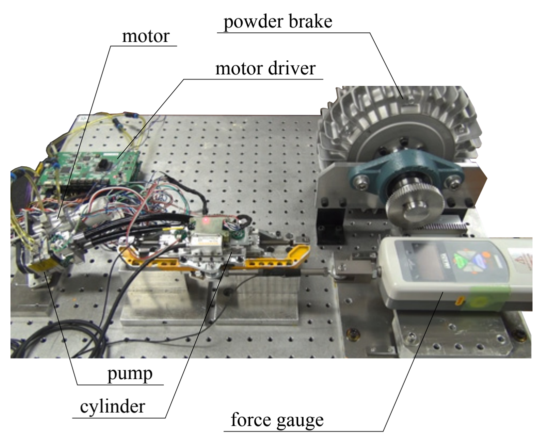

Fig. 3. Setup for the Experiment to Investigate the Loss of EHA

The losses of EHA in the experiment is shown in Fig.4. The horizontal axis represents the load given to the cylinder, and the vertical axis represents the energy. It was confirmed that the internal leakage loss and the viscous friction loss increased greatly as the load increased while the change of the coulomb friction loss was small. Therefore, it is necessary to reduce the internal leakage loss and the friction loss to improve the energy efficiency of the high-pressure pump because these losses are dominant under high pressure.

V. FORMULATION OF EACH LOSS OF THE PUMP

A. Internal Leakage Loss

As shown in Fig.2, the gap ① exists in two places, gap A and gap B. Gap A is between casing X and the gear, and gap B is between casing Z and the gear. Internal leakage occurs in each gap, so the total internal leakage amount is the sum of each. When differential pressure is generated in

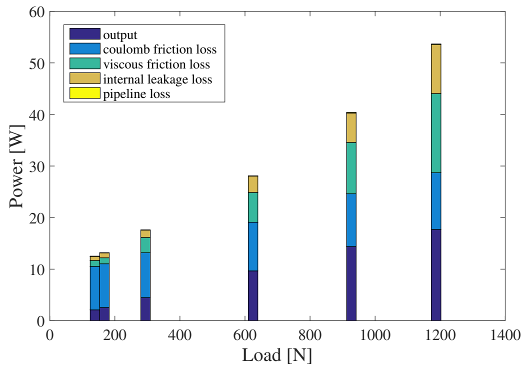

Fig. 4. Relation between the Cylinder Load and Energy Losses of EHA (Cylinder speed is 15 mm/s)

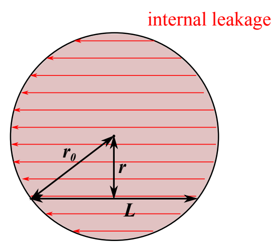

Fig. 5. The Disk Approximated from the Tooth Profile of the Gear to Calculate Internal Leakage at the Gap A and B

the pump, the internal leakage flow in the gap ① can be assumed to be Poiseuille flow. The flow rate of the two-dimensional Poiseuille flow $\hat{q}$ is given as

$$\hat{q} = \frac{\Delta p}{12\mu L}x^3 \tag{1}$$

where Δp is the differential pressure, x is the gap width and μ is the viscosity of the fluid, L is the length of the internal leakage flow path. From Fig.5, L can be expressed as $L = 2\sqrt{r_0^2 - r^2}$. Approximating the gear as the disk like Fig.5, the flow rate of the internal leakage flow at the gap ① can be expressed as

$$\begin{aligned}\hat{q}_c &= \int_{-r_0}^{r_0} \frac{\Delta p}{12\mu L}x^3 dr \\ &= \frac{\pi x^3}{24\mu}\Delta p\end{aligned} \tag{2}$$

where r_0 is the radius of the disk. The sum of the internal leakage flow rate in the gap A and the gap B can be expressed as

$$q = \frac{\pi(x_A^3 + x_B^3)}{24\mu}\Delta p \tag{3}$$

Subscript 'A' and 'B' represent the gap A and the gap B respectively. The internal leakage loss E_q is expressed as

$$E_q = \Delta p q \tag{4}$$

From (3), the internal leakage loss can be expressed as

$$E_q = \frac{\pi(x_A^3 + x_B^3)}{24\mu}\Delta p^2 \tag{5}$$

Internal leakage loss can be expressed as the quadratic equation of the differential pressure. In order to reduce the internal leakage loss, it is effective to reduce the gap width and to use a large viscosity hydraulic fluid.

If the internal pressure of the pump is high, there is a possibility of casing deformation. Regarding internal leakage in the gap ①, we considered that the deformation amount of the casing Δx is proportional to the internal pressure of the pump p as (6). The pressure receiving area of the casing is A and the rigidity of the casing is k. When the differential pressure Δp is generated in the pump, the pressure on the high pressure side is $p + \frac{\Delta p}{2}$ and the pressure on the low pressure side is $p - \frac{\Delta p}{2}$ where internal pressure is p.

$$pA = k\Delta x \tag{6}$$

From (6), the deformation amount Δx can be expressed as

$$\Delta x = \frac{Ap}{k} \tag{7}$$

Considering deformation of the casing, the internal leakage amount in the gap A and B increases which can be expressed as

$$q = \frac{\pi((x_A + \Delta x)^3 + (x_B + \Delta x)^3)}{24\mu}\Delta p \tag{8}$$

From (7), the relation between the internal leakage amount q and the internal pressure p is expressed as.

$$q = \frac{\pi((x_A + Ap/k)^3 + (x_B + Ap/k)^3)}{24\mu}\Delta p \tag{9}$$

Internal leakage loss at the gap ① can be expressed as

$$E_q = \frac{\pi((x_A + Ap/k)^3 + (x_B + Ap/k)^3)}{24\mu}\Delta p^2 \tag{10}$$

Since the internal leakage loss includes the minus cube of the rigidity of the casing, it is considered to be effective increase the rigidity of the casing for suppressing an increase of internal leakage loss.

B. Viscous Friction Loss

When we approximated a gear to a disk like Fig.5, shear stress is given by $\tau = \mu\frac{\partial v}{\partial x}$ where v is the speed and x is the displacement of the width direction of the gap. The viscous friction torque caused by the internal leakage at the gap ① is approximately expressed as

$$\tau_v = \iint_S \mu\frac{\partial v}{\partial x} r dy dz \tag{11}$$

Since viscous friction due to internal leakage occurs in each of the gap A and B, the viscous friction loss can be expressed as

$$\tau_v = \frac{\mu \pi r_0^4}{2x_A}\dot{\theta} + \frac{\mu \pi r_0^4}{2x_B}\dot{\theta} \tag{12}$$

where $\dot{\theta}$ is the rotational speed of the pump. Here, we considered that the flow in a rotational direction is the Couette flow. The viscous friction loss E_v is expressed as the product of the viscous friction torque τ_v and the rotational speed $\dot{\theta}$ as (13).

$$E_v = \tau_v \dot{\theta} \tag{13}$$

Assuming a simple system in which the inlet and the outlet of the pump is closed, the internal leakage flow rate can be expressed as (14) because the discharge volume is equal to the internal leakage amount.

$$q = k_d \dot{\theta} \tag{14}$$

where k_d is the discharge per 1 rad. The rotational speed of the pump to generate differential pressure Δp is determined to be (15) from (3) and (14).

$$\dot{\theta} = \frac{\pi(x_A^3 + x_B^3)}{24\mu k_d}\Delta p \tag{15}$$

From (12) (13) (15), the viscous friction loss can be expressed as

$$E_v = \frac{\pi^3 r_0^4 (x_A + x_B)(x_A^3 + x_B^3)^2}{1152 \mu k_d^2 x_A x_B}\Delta p^2 \tag{16}$$

From (16), it is considered to be effective for loss reduction to reduce the gap width, to increase the discharge amount per 1 rad, to make the radius of the gear smaller and to use a large viscosity hydraulic fluid.

VI. METHOD TO IMPROVE PUMP DESIGN TO REDUCE LOSSES

Since the internal leakage loss and the viscous friction loss are thought to be dominant under high pressure, we focused on these losses. From (5), in order to reduce the internal leakage loss, it is necessary to reduce the gap width and to increase the viscosity of the oil. From (16), in order to reduce the viscous friction loss, it is necessary to reduce the gap width, to increase the discharge amount per 1 rad, to make the radius of the gear smaller and to increase the viscosity of the oil. It is especially important to reduce the gap width because making gaps small contributes to both losses. In order to reduce the internal leakage loss and the viscous friction loss, we designed the pump focusing on the following two points.

- Increase the pump discharge amount per 1 rad keeping the radius of the gear small.

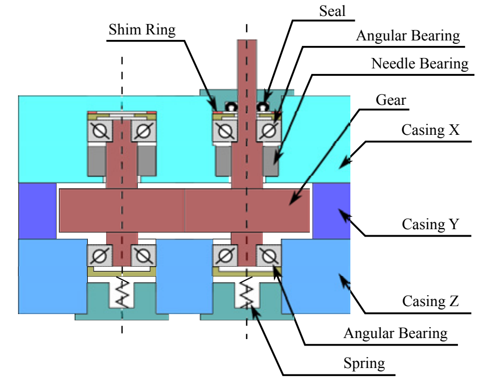

Fig. 6. Schematic Drawing of Cross Sectional View of Developed Involute External Gear Pump

TABLE I

PARAMETERS OF THE PUMPS.

	Trochoid Pump	Involute Pump
Weight [g]	182	227
Size [mm]	$74.8 \times 37.5 \times 52.5$	$58.5 \times 47.2 \times 42$
Discharge Amount [mm^3]	418	832

- Reduce the gap width.

We designed the pump to be a similar size to the conventional trochoid pump. We adopted the involute external gear pump which has about twice the discharge amount per 1 rad of the conventional trochoid pump while the size of each pump is similar as shown in Table.I.

In the conventional trochoid pump, there are three gaps to adjust the number of shim rings as shown in Fig.2. Since gaps of conventional trochoid pump depend on the width of shim rings, we considered that the gap width can be made smaller than before by removing the assembly error by determining the sum of the gap width with the processing accuracy. In our design as shown in Fig.6, the sum width of the two gaps is determined by the thickness of the casing Y and the thickness of the gear. And the allocation of the two gaps is adjustable by using the shim rings of $10\mu\mathrm{m}$ thick. The weight and size of the developed involute external gear pump are shown in Table.I, which is a close size to the conventional trochoid pump.

VII. VERIFICATION TEST FOR LOSS REDUCTION OF DEVELOPED PUMP

We conducted the experiments using conventional trochoid pump and developed involute external gear pump to investigate the internal leakage loss and the viscous friction loss of each pump. In this experiment, we calculated each loss changing the differential pressure. We used the pump whose inlet was connected to the oil tank and outlet was closed. About the trochoid pump, we changed the number of shim rings Ⅲ to evaluate the effect of $10\mu\mathrm{m}$ difference of gap width. As shown in Fig.7, torque is transmitted from the electric motor to the input shaft of the involute external gear pump via the reducer. There is an encoder to obtain the rotational speed of motor, a pressure sensor to acquire the

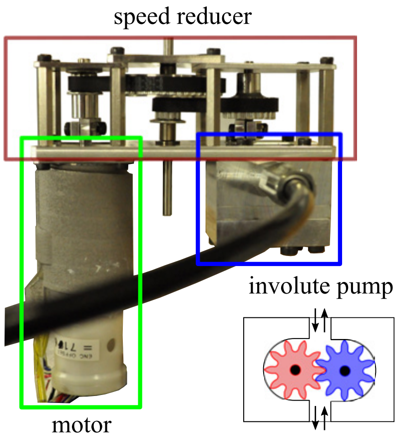

Fig. 7. Developed Involute External Gear Pump Used for the Experiment (Reduction ratio of speed reducer is 1: 8.)

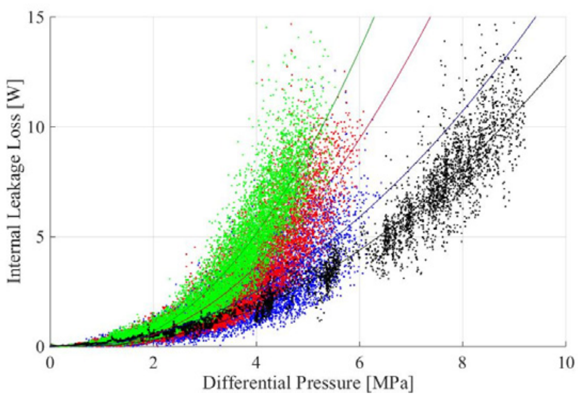

Fig. 8. Relationship between Differential Pressure and the Internal Leakage Loss of the Pumps. Black: involute external gear pump. Blue: trochoid pump, Red: trochoid pump (gap B +10μm), Green: trochoid pump (gap B +20μm). Pumps of red and green data has extra 1 or 2 shim rings II compared to the pump of blue data. The curve represents the regression curve of the differential pressure squared referring from (5).

pressure of the pump, a current sensor to acquire the input current to the motor.

The relationship between differential pressure and the internal leakage loss is shown in Fig.8 and the relationship between differential pressure and viscous friction loss is shown in Fig.9. The internal leakage loss and the viscous friction loss at 6MPa and 10MPa are shown in Table.II, Table.III respectively. Each loss is obtained by using a regression curve. The internal leakage loss is reduced by 25.7% at 6MPa and 22.4% at 10MPa. The viscous friction loss is reduced by 87.3% at 6MPa and 85.6% at 10MPa. In particular, the viscous friction loss was greatly reduced.

A Difference of 10μm in the gap has a large influence on each loss. For example, comparing the trochoid pump of blue data and that of red data whose width of the gap B is 10μm wider than the trochoid pump of blue data, the internal leakage loss increased by 60.1% at 6MPa. Therefore, it was confirmed that the gap difference of 10μm has a large influence on the loss.

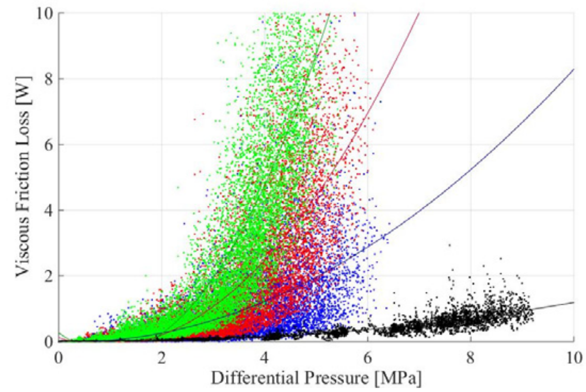

Fig. 9. Relationship between Differential Pressure and the Viscous Friction Loss of the Pumps. Black: involute external gear pump. Blue: trochoid pump, Red: trochoid pump (gap B +10μm), Green: trochoid pump (gap B +20μm). Pumps of red and green data has extra 1 or 2 shim rings II compared to the pump of blue data. The curve represents the regression curve of the differential pressure squared referring from (16).

TABLE II
THE INTERNAL LEAKAGE LOSS OF INVOLUTE EXTERNAL GEAR PUMP AND TROCHOID PUMP

Differential Pressure [MPa]	6	10
Involute Pump [W]	4.39	13.2
Trochoid Pump [W]	5.91	17.0
Trochoid Pump (Gap B +10μm) [W]	9.46	29.1
Trochoid Pump (Gap B +20μm) [W]	13.5	41.9

TABLE III
THE VISCOUS FRICTION LOSS OF INVOLUTE EXTERNAL GEAR PUMP AND TROCHOID PUMP

Differential Pressure [MPa]	6	10
Involute pump [W]	0.366	1.19
Trochoid pump [W]	2.88	8.29
Trochoid pump (Gap B +10μm) [W]	6.96	22.5
Trochoid pump (Gap B +20μm) [W]	13.9	45.8

VIII. DESIGN METHOD FOR SUPPRESSING INCREASE IN INTERNAL LEAKAGE LOSS

In order to prevent an increase in internal leakage loss caused by the increase of the gap, a method to prevent deformation of the casing by enhancing the rigidity of the casing is effective. We adopted a method of using fine ceramics which is a high rigidity and lightweight material for the casing. Young's modulus of alumina ceramics is about twice that of iron and the density of alumina ceramics is about a half of that of iron.

We conducted the experiment using two type of pumps: one is the trochoid pump whose casing X is made of alumina ceramics as shown in Fig.10, the other is the conventional trochoid pump whose casing X is made of aluminum alloy. In the experiment, the inlet and outlet of the pump is closed in order to measure the internal leakage amount easily. The internal leakage amount is equal to the discharge amount in this setup. We changed only the internal pressure to evaluate

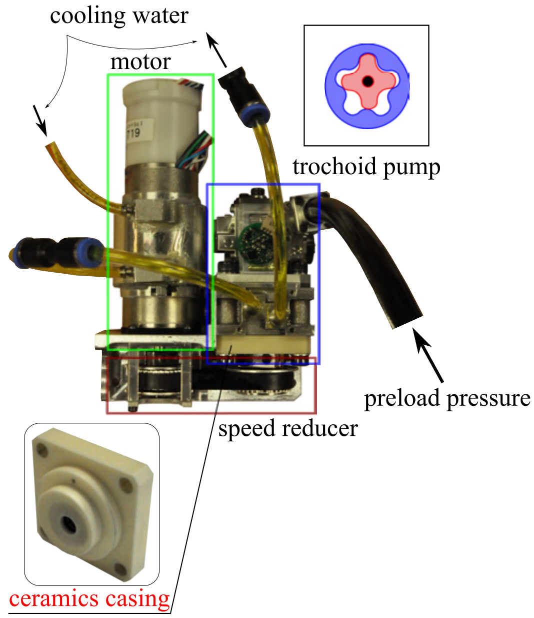

Fig. 10. Experimental Device of the Trochoid Pump Using Fine Ceramics as a Casing Material

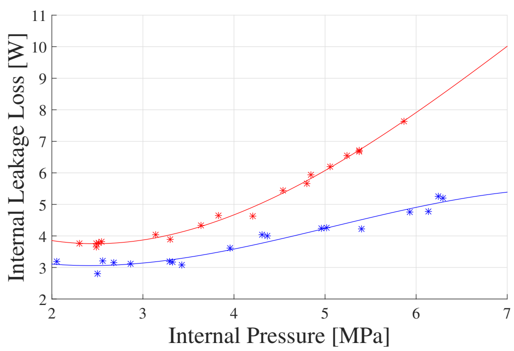

Fig. 11. Relationship between Internal Pressure and Internal Leakage Loss: red data is the aluminum-casing pump, blue data is the ceramic-casing pump. The curve represents the regression curve approximated by a cubic function of the internal pressure referring from (10).

the effect of the internal pressure to the internal leakage loss. The internal pressure is determined by the preload pressure.

The relationship between internal pressure and internal leakage loss is shown in Fig.11. From this graph, the increase in internal leakage loss of the pump using ceramics-casing is smaller than that of the pump using aluminum-casing. The increase in internal leakage loss of the pump using ceramics-casing was 56.2% less than that of the pump using aluminum-casing when the internal pressure increased from 3MPa to 6MPa.

IX. CONCLUSION

We formulated the internal leakage loss and the viscous friction loss respectively. As a result, we found that the width of the gap inside the pump has a large influence on the internal leakage loss and found that the width of the gap inside the pump and the discharge amount per 1 rad influence the viscous friction loss. Then, we investigated the distribution of the energy losses of EHA. It was confirmed that the internal leakage loss and the viscous friction loss are dominant under high pressure. We designed the pump to reduce the internal leakage loss and the viscous friction loss. We adopted an involute external gear to increase the discharge amount per 1 rad keeping the radius of the gear small. About the developed involute external gear pump, the internal leakage loss is reduced by 22.4% at 10MPa and the viscous friction loss is reduced by 85.6% at 10MPa.

About a problem of the increase in internal leakage loss due to the deformation of the casing under high pressure. From the formulation of the internal leakage loss considering the deformation of the casing, we found that it is necessary to enhance the rigidity of the casing in order to suppress the increase in internal leakage. Therefore, we developed the pump using ceramics as a rigid and lightweight material for the casing. Compared with the pump using aluminum-casing, the pump using ceramics-casing reduced 56.2% in internal leakage loss when the internal pressure increased from 3MPa to 6MPa. It was confirmed that enhancing the rigidity of the casing is an effective method to suppress the increase in internal leakage loss.

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