DEVELOPMENT OF A NEW VARIABLE DISPLACEMENT PUMP/MOTOR UNIT AND ITS APPLICATION TO THE HYDRO- MECHANICAL TRANSMISSION

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ABSTRACT

One major factor which decides the performance of hydraulic continuously variable transmission, is a pair of pump/motor. We have developed a compact, light, and very efficient pump/motor unit, the structure of which bases on a new concept and is completely different from the conventional ones.

And as its application, the hydro-mechanical transmission is also developed.

The transmission is compact, light and fuel-saving. This thesis describes outline of their construction and operation.

KEYWORDS

hydro-mechanical transmission
variable pump/motor

INTRODUCTION

The need for easy driving has resulted in the drastic increase of car with automatic transmission these days.

At the same time, the electronic control techniques have advanced tremendously, and the hydraulic continuously variable transmissions which allow easy electronic control are considered to have more advantages than other transmissions.

Now we have developed a variable displacement pump/motor unit basing on a new concept, and as its application, produced the automotive Hydro-Mechanical Transmission (HMT) incorporating new trials. We will first introduce this new variable displacement pump/motor unit, then explain about its hydro-mechanical transmission.

THE VARIABLE DISPLACEMENT PUMP/MOTOR BASED ON A NEW CONCEPT

In the hydraulic continuously variable transmission, the transmission of power and speed control are done by a pair of pump/motor, and the pump/motor are desired to have the following performance

1) High Efficiency

As the continuously variable transmission for automobile is usually operated at fractional power, the pump/motor also needs to be high efficient at partial loading.

2) Reversible Function

A pair of pump/motor needs to exchange each function. This will make the transmission more efficient and widen the speed range.

3) Good Motor Performance

Good starting torque and low speed performance are required for the motor.

4) Fine and Fast control of displacement

5) Light and Compact

6) Little Vibration and Noise

In order to realize the above described performance, we have developed the pump/motor basing on the new concept, by which the structure is completely different from the conventional ones.

This newly developed pump/motor is the variable displacement radial piston pump/motor based on the concept of "Fluid Force Couple".⁽¹⁾ (Fig 1) This pump/motor has the following characteristics:

- 1) In this pump/motor, all hydraulic forces are balanced statically, and all the sliding contact surfaces are supported by fluid pressure. As a result, it realizes little mechanical loss and high efficiency even at partial loading. (Fig 2)

Fig2 EFFICIENCY OF PUMP

- 2) As the F.F.C design can eliminate heavy duty shaft bearings, this pump/motor is very compact and light as much as half or thirds of the conventional ones. (Fig 3)
- 3) As the pressure is exerted on both sides of a piston equally, the tilting moment of the piston is eliminated. And small radius distributor contributes to high speed operation -- $C_p=15000$ to 18000 -- (Fig 4)
- 4) This pump/motor is silent because cylinders are located radially and total force by pressure is constant at any rotational angle.
- 5) The displacement of pump/motor is controlled by the servo valve built in the pintol. As the servo valve is driven by a step motor directly, fast and precise control is realized.

Fig3 WEIGHT OF PISTON PUMP/MOTOR AS FUNCTION OF DISPLACEMENT⁽²⁾

Fig4 MAX. SPEEDS OF PISTON PUMP/MOTOR AS FUNCTION OF DISPLACEMENT

In this study, we also developed "Hydraulic Unit" incorporating one pair of pump/motor, one step motor for control, two relief valves, and other valves, to make it compact and maintenance easy. (Fig 5)
In the "Hydraulic Unit", the pump/motor connected with the Lo-shaft of the transmission is called "Unit-S", and that with the Hi-shaft "Unit-R". (Fig 6)

Fig5 CONFIGURATION OF HYD.UNIT

Fig6 DIMENSION OF HYDRAULIC UNIT

EXPERIMENTAL PRODUCT OF HMT INCORPORATING "HYDRAULIC UNIT"

Incorporating the "Hydraulic Unit", an automotive hydro-mechanical transmission has been developed. (Table 1, Fig 7)
The configuration of gear train is same as that of Orshansky's transmission⁽²⁾.
The test vehicle is an FF type passenger car of 1800cc.

Table 1 SPECIFICATION OF
THE DEVELOPED HMT

PURPOSE	100PS FF CAR
STRUCTURE	SINGLE INPUT-SPLIT TYPE
MODE	REVEASE MODE LO-SPEED MODE MIDDLE LOCK-UP MODE HI-SPEED MODE TOP LOCK-UP MODE
MODE CHANGE	BY SYNCROMESH CLUTCH
ENGINE CONTROL	ENGINE OPTIMAL CONTROL
CONTROL UNIT	8BIT MICROCOMPUTER
WEIGHT	72Kg (DRY) (INCLUDING HYD.UNIT)
DIMENSION	388(L)*548(W)*388(H)
HYD.UNIT	RADIAL PISTON PUMP/MOTOR DISPLACEMENT 50cc/revmax PRESSURE 30MPa max MAX SPEED 5000rpm(cont) 6000rpm(int.) WEIGHT 23Kg (DRY)

Fig7 DIMENSION OF TRANSMISSION

Fig9 CONTROL DIAGRAM

OPERATION OF HMT

a) Start

At start, just before the unit pressure reaches the relief pressure, the accel modulator operates, and lessens the throttle opening.

This operation eliminates the unnecessary fuel consumption and prevents the heating of the Hydraulic Unit.

b) Lo-speed mode

At Lo-speed mode, the Lo-Clutch (CL) is engaged on the output shaft, and the Hi-Clutch (CH) is disengaged. The Unit-R is pump operation and the Unit-S is motor operation.

That is, the ring gear of the planetary gear drives the Unit-R. The Unit-S is driven by the hydraulic energy and the torque from the sun gear are combined at the Forward-Clutch (CF) to be output through the Lo-clutch.

When the ratio of the Unit-S Displacement (DS) and the Unit-R Displacement (DR) is increased, the output shaft speed increases, as a result, the car velocity also increase. As the output speed increase, the Speed of Lo-clutch (SL) and the Speed of Hi-clutch (SH) become closer. (Fig 10, Fig 11)

c) Middle lock-up mode

When SL and SH become closer to a certain degree, the HMT control unit controls DS to make SL and SH equal. When the speeds of both clutches become equal, the Hi-clutch is engaged.

A slight increase in DS will make the pressure of the Hydraulic Unit minimum and a half of the transmission torque is transmitted by the Hi-clutch. In this condition the Hydraulic Unit will no more transmit the power and all the power is transmitted through the gear train.

When the accel is added down or the running resistance increases, shift down to Low-speed mode is required. Then the HMT control unit will make all the torque transferred to the Lo-clutch and hence disengages the Hi-clutch.

On the otherhand, when the accel is released or the car speed increases, it operates to shift up to the High-speed mode.

In the transition to the Hi-speed mode, the Unit-R and the Unit-S have to exchange the function of pump/motor, and the displacement of the Unit-S is increased slightly.

Fig10 HYD. UNIT DISPLACEMENTS AS FUNCTION OF TRANSMISSION SPEED RATIO

Fig11 CLUTCH SPEEDS AS FUNCTION OF TRANSMISSION SPEED RATIO

In proportion to the displacement change of the Unit-S, the torque transmitted through the Lo-clutch decreases, and the torque transmitted through the Hi-clutch increases. When the torque transmitted through the Lo-clutch becomes zero, the Lo-clutch is disengaged.

In this way, the engine torque is transferred from Lo-clutch to Hi-clutch continuously, and the smooth, shockless mode change is achieved.

d) High-speed mode

At High-speed mode, the Hi-clutch is engaged on the output shaft, and the Unit-S functions as pump and Unit-R as motor. That is, the sun gear drives the Unit-S.

The torque from the Unit-R which is driven by the hydraulic energy, and that from the ring gear are combined and put out through the Hi-clutch. Contrary to the Low-speed mode, the decrease of DR/DS makes the increase of speed ratio.

e) Top Lock-up mode

When the speed ratio approaches to about 1.4, i.e. SL approaches to zero, the HMT control unit controls DR to bring SL to zero. As a result, the Unit-S stops and only sustains the reaction of the sun gear by the differential pressure of the Hydraulic Unit.

Then after the Reverse-Clutch (CR) constrains the Unit-S, by making the Unit-R displacement zero, the circuit pressure becomes minimum and the Hydraulic Unit can be out of operation.

This results in the decrease of the power loss, and improves the system efficiency and reliability.

f) Reverse mode

Reverse mode may be possible by making the Unit-R displacement negative, maintaining the same clutch condition of the Lo-speed mode.

But pure Hydro-static type, which transmits the Unit-S output directly to the output shaft by fixing the sun gear, is more preferable.

That means after engaging the Reverse-clutch, relieve the Forward-clutch and reverse the displacement of the Unit-R. The engine torque can be put out to the axle shaft through the Unit-R and the Unit-S.

Fig12 ESTIMATION OF TRANSMISSION EFFICIENCY

(ENG. speed 1450rpm, torque 7.3kgf·m)
(accel position 1/8)
(pump/motor data is actually measured)

RUNNING RESULT

Most of the running tests were principle carried out on chassis dynamometer and the function were confirmed. The actual engine speed was fairly close to the target speed, and there was no mode change shock and the control of the transmission was quite satisfactory.

Based on the experimental data of the hydraulic unit, Fig 12 indicates the calculation result of the system efficiency assuming the loss of gear is 1.5% at each stage. The fuel efficiency and acceleration calculated by simulation based on the actual data of the hydraulic unit, was better than those of 4AT.

AFTERWORD

The outline of the new hydraulic unit and the hydraulic continuously variable transmission has been described. They are still on the first level of the development and there are still rooms for improvements. We will certainly keep working on them.

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