Verification of Centrifugal Pawl Clutch (CePaC) on Two-speed Transmission by Vehicle Test

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ABSTRACT: The spread of electric vehicles is required in response to the demand for carbon neutral society. Therefore, it is desired to reduce the cost of electric motors and powertrains. In response to such demands, we verified the possibility of a simple two speed transmission that can bring out driving performance while constructing a powertrain with a down-sizing motor. Centrifugal Pawl Clutch (CePaC) is used for the two speed transmission. This paper describes the principle of shifting mechanism, traction motor torque control method, and the experimental results of the vehicle test.

KEY WORDS: 2 speed EV, down-sizing motor, simple motor control, Centrifugal Pawl Clutch without actuator

1. INTRODUCTION

The widespread use of electric vehicles is required in response to meet the demand for carbon neutral society. For this expanding use of electric vehicles, it is desired to reduce the development lead time, the overall cost, and the cost of electric powertrain itself. In response to such demands, we verified the possibility of a small motor, in other words, a down-sizing motor with a simple two speed transmission.

As the background of the down-sizing motor concept, if an existing motor and inverter which are already installed into the series production passenger cars can be utilized, then the motor and inverter development lead time as well as the efforts and the cost can be removed, also the cost of eAxle itself could be reduced.

The concept of down-sizing motor with two speed eAxle can provide increased torque similar to the torque mode by high reduction gear ratio even though the motor is relatively small size, or voltage compare with the vehicle weight. Although generally speaking, larger vehicles such as commercial vehicles, pick-up trucks and high-performance cars require a high-performance motor such as bigger torque or a high rotation speed with high voltage.

To realize the down-sizing motor concept, we developed a one-way clutch (OWC), called the Centrifugal pawl clutch (CePaC), and an electric-controlled clutch pack, called the eCuPa. Then, we designed a simple two speed parallel type transmission. The transmission is controlled by a simple motor control which can also contribute to save the drive system development lead time. As the key mechanism, the transmission is composed of a CePaC for torque mode gear connection and an eCuPa for normal mode gear connection. The torque mode gear is used in the situation of bigger torque requested such as first gear or the vehicle in the backward direction. The normal gear is used in normal situation such as second gear.

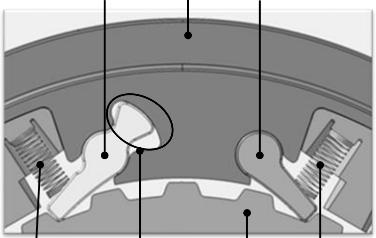
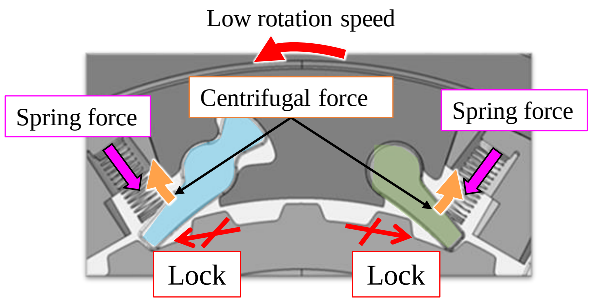


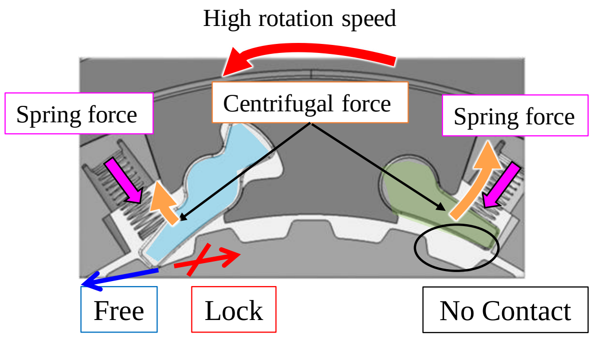
Fig. 1 Structure of CePaC

Generally, electric vehicles are required to meet higher demands on vibrations and shocks. In response to such demands, there is a method of applying feedback control while measuring the torque of the output shaft with a torque sensor (1). However, the combination of CePaC and eCuPa achieves the seamless shifting by using one-way clutch function in CePaC installed in the gear.

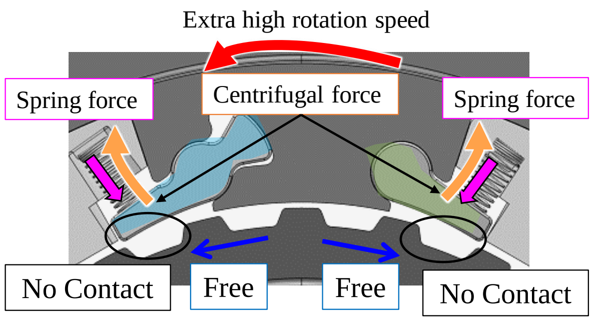
The traction motor is controlled not by rotational speed control. The motor has only torque control also in the situation of gear shifting transition by using the one-way clutch function. One-way



(a) Front view of CePaC in Lock mode



(b) Front view of CePaC in OWC mode



(c) Front view of CePaC in Free mode

Fig. 2 Mechanism of changing mode of CePaC

clutch function does not require precise motor rotational speed control since the one-way clutch ratcheting mechanism accepts rough synchronization of rotation speeds during the clutch engagement. We verified that an inexpensive motor with no precise control achieves shock-free shifting by using the one-way clutch function (2).

This paper describes CePaC and eCuPa and the structure of a simple two speed transmission using them, as well as the test results of the vehicle with two speed transmission.

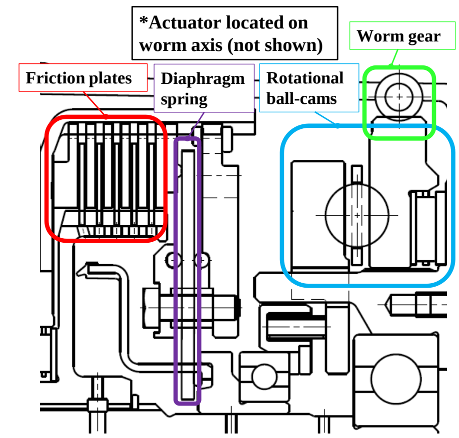
2. CENTRIFUGAL PAWL CLUTCH (CePaC)

OWC allows free rotation in one direction and transmits torque in the opposite direction. In addition to the OWC function, the CePaC also has the functions of either transmitting torque in both directions and not transmitting torque in both directions. And these three functions can be controlled by centrifugal force. Figure 1 shows the structure of the CePaC. The CePaC consists of Pawls for Lock, Pawls for OWC, an inner ring, an outer ring and springs.

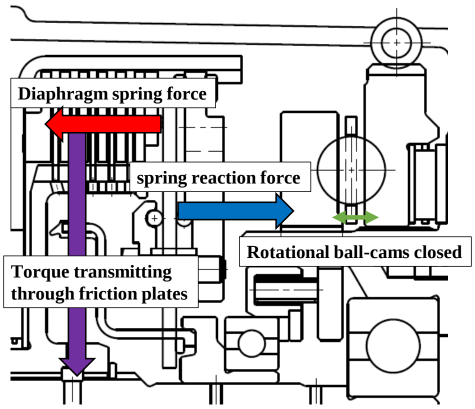
Figure 2 shows the mechanism for selecting CePaC functions. Figure 2 (a) shows the pawl posture when the CePaC in Lock mode. At that time, the rotation speed of the outer ring is low and the CePaC is able to transmit torque in both directions since both pawls engage with the inner ring by the spring force. Figure 2 (b) shows the pawl posture when the CePaC in OWC mode. At that time, the rotation speed is high, and the Pawl for Lock does not engage with the inner ring due to the centrifugal force exceeds the spring force. On the other hand, the Pawl for OWC engages with the inner ring due to the centrifugal force is not exceeding the spring force as the center of gravity and rotational center of the Pawl for OWC are designed short. Therefore, the CePaC is in OWC mode. Furthermore, at higher rotational speed, the Pawl for OWC also does not engage with the inner ring, since the centrifugal force is large. As the result, CePaC is in Free mode. Figure 2 (c) shows the pawl posture when the CePaC in Free mode. In Free mode, the outer ring and the inner ring are not in contact at all. As a result, it prevents the fatigue or wear on the pawl. It helps to reduce drag torque. The threshold rotational speed of mode change can be designed by the shape, dimensions of the pawl and the spring force. In this prototype transmission, the pawls are designed to shift Free mode when the vehicle drives above 60km/h in High gear.

3. ELECTRIC-CONTROLLED CLUTCH PACK (eCuPa)

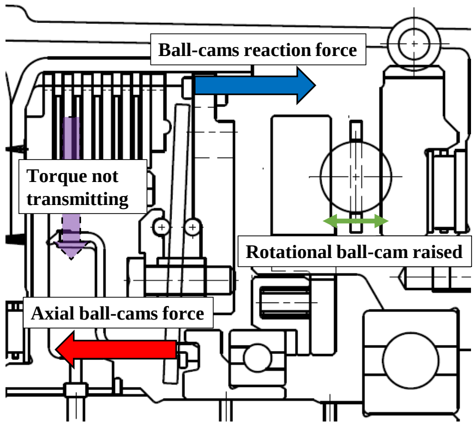
Typical clutch packs use a hydraulic piston to control the transmitting torque. We developed an electric-controlled Clutch Pack, called eCuPa, as a component of the transmission for EVs. Figure 3 (a) shows the structure of the eCuPa. eCuPa is operated by an electric motor and a diaphragm spring instead of a hydraulic piston. For the details, the actuator motor torque is converted to the axial force by a worm gear and a rotational ball-cams. The torque through eCuPa is then controlled by the pressure force generated by the diaphragm spring which is operated by the actuator motor. Figure 3 shows the state of eCuPa being closed in (b) and opened in (c). The eCuPa in the system is normally used in the closed(connected) condition, it is designed that the diaphragm spring force is applied as the normal condition to save the actuator electricity consumption. Therefore, eCuPa has an advantage that can remove the hydraulic pump system and saving energy consumption for holding the condition of the clutch pack connection.



(a) Cross section view of eCuPa



(b) Force diagram of eCuPa in the close state



(c) Force diagram of eCuPa in the open state

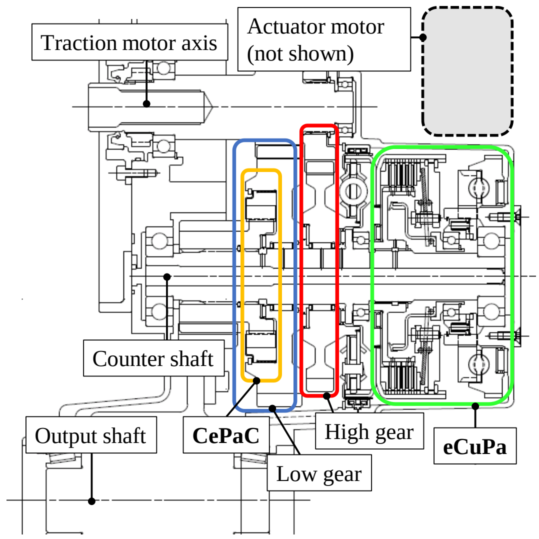
Fig. 3 Structure of eCuPa

4. TWO-SPEED TRANSMISSION WITH CePaC

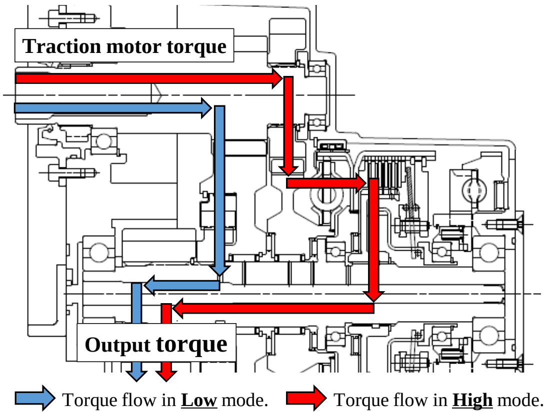
4.1 Composition

There are many possible compositions of transmission using the CePaC and the eCuPa. In this paper, a parallel type transmission is proposed.

Figure 4 (a) shows the structure of the proposed parallel type transmission. The Low and High gears are attached to the traction motor axis (the Input shaft) and are always engaged with the Low and High driven gears on the counter shaft. The counter shaft and



(a) Cross section view of 2-speed transmission



(b) Traction motor torque flow in 2-speed transmission

Fig. 4 Structure of 2-speed transmission

the Low driven gear are connected through the CePaC, and the second shaft and the High driven gear are connected through the eCuPa.

When the transmission is in the Low mode, the eCuPa is in opened condition and the traction motor torque is transmitted through the Low gear and the CePaC. On the other hand for the High mode, the eCuPa is connected by the actuator for the traction motor torque is transmitting through the High gear and the eCuPa.

4.2 Gear shift strategies

The gear shifting is basically operated automatically. The High or the Low mode is selected by the output torque and the vehicle speed. The output torque is estimated from the shift position of the transmission and the torque command signals from the vehicle. Figure 5 shows the shift control map.

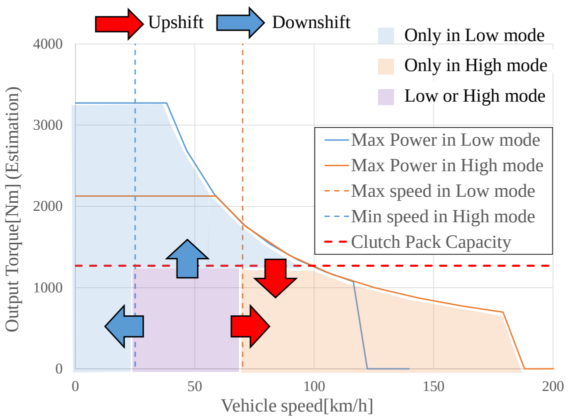


Fig. 5 Shift control map

4.3 Torque control method for shifting

Generally speaking, automatic transmissions use friction plates clutch, and the gear shifting is achieved smoothly by the feedback control of the clutch and the engine torque control. In this transmission, smooth gear shifting can be achieved only by torque control of the traction motor without feedback control of the actuator motor for the friction plates clutch. It means that no precious position control or the pressure control are required for the friction plates clutch connection, so that an inexpensive actuator motor is utilized as the clutch actuator helping for the cost saving.

1) Upshifting (shifting from the Low mode to the High mode)

When the CePaC rotation speed is reached to a designated speed, upshifting is started by the operation of the eCuPa to closed condition. The control method of the eCuPa connection is to reduce the traction motor torque in the inertia phase.

2) Downshifting(shifting from the High mode to the Low mode)

When the CePaC rotation speed is decreased to a designed speed, downshifting is started by the operation of the eCuPa to opened condition and raising the traction motor speed. When the traction motor speed is reached up to the Low mode speed, the CePaC automatically engages, and the vehicle shifts to the Low mode. To increase the traction motor rotational speed by the motor torque control is applied for the downshifting.

5. EXPERIMENT

5.1 Composition of the prototype transmission

To evaluate the prototype transmission and the control method, the transmission was installed into a series production electric passenger vehicle. And we named the prototype transmission NW2SP. Figure 6 shows the outer appearance of NW2SP. NW2SP is simply designed. Table 1 shows the main specs of NW2SP.

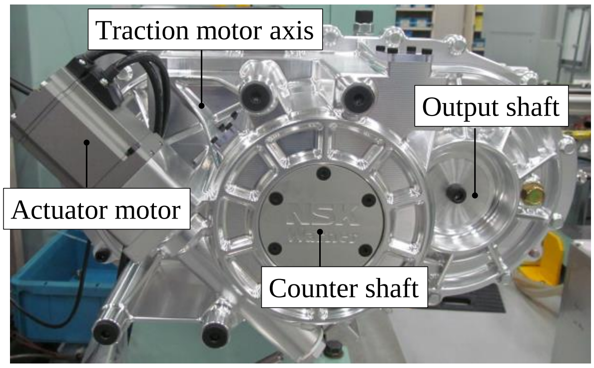


Fig. 6 NW2SP (prototype of two speed transmission)

Table1 Specifications of the prototype (NW2SP)

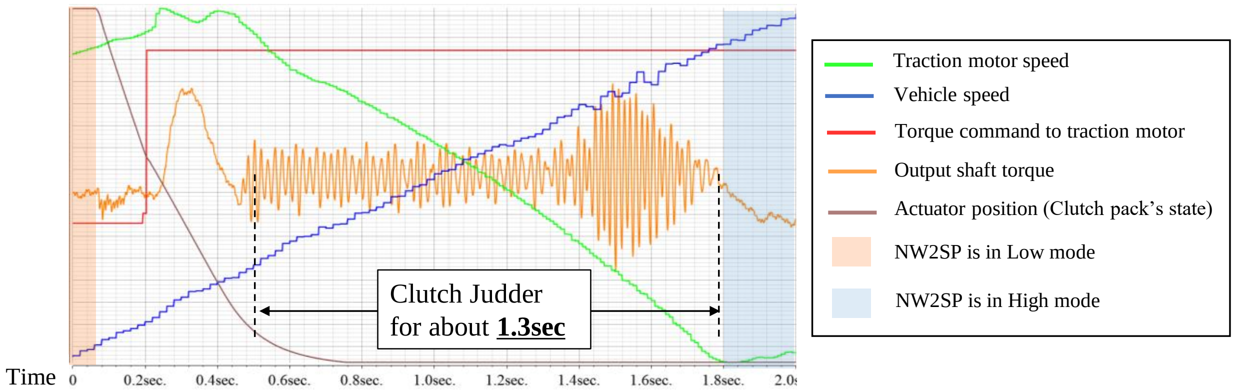
	NW2SP
Width(mm)	520
Height(mm)	290
Length(mm)	324
Mass(kg)	45
Lubricant Volume(L)	1.4
Type of transmission	Parallel axis
Reduction Gear Ratio	10.23(Low) 6.65(High)
Torque transfer components	**CePaC** (Low) **eCuPa** (High)

5.2 Experimental setup

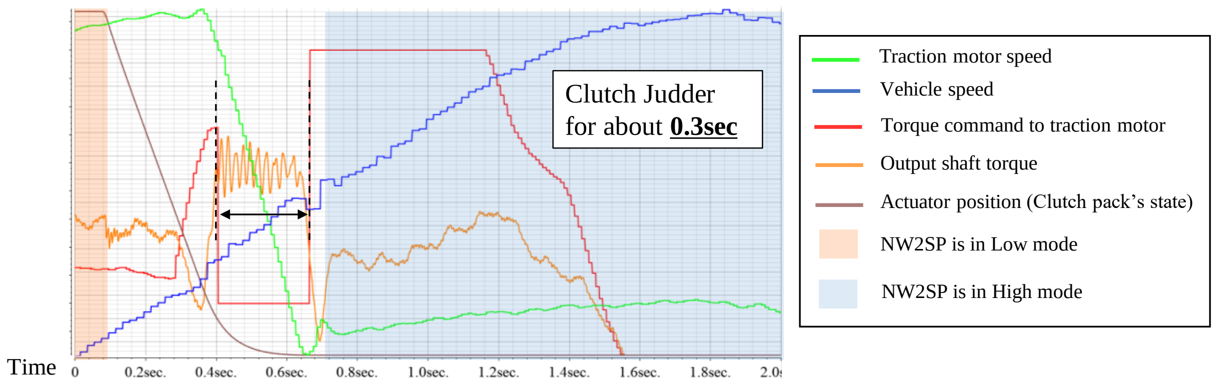
The RCP system (MicroAutoBoxII, dSPACE) is used for the control of the prototype transmission and also the traction motor. The RCP system monitors the rotation angle of the actuator motor to recognize the state of the transmission. CAN signals between the Vehicle Control Module and the Inverter unit is used for the recognition of the state of the vehicle. The system controls the traction motor by CAN signals during the gear shifting. In this system, the signal sampling speed and the calculation cycle are 1ms and CAN signals are sent in 10ms intervals. A servo motor (NX620, Oriental Motor) was used as the actuator even though the motor is operated by fixed speed.

5.3 Vehicle test

The shifting timing from the Low mode to the High mode is set by 70 km/h and the regeneration is able in the High mode. When the vehicle speed is reduced from e.g. 100 km/h to 40 km/h,



(a) Upshifting using only the step control



(b) Upshifting applied the ramp control and the torque reduction

Fig. 7 Experiment results of upshifting

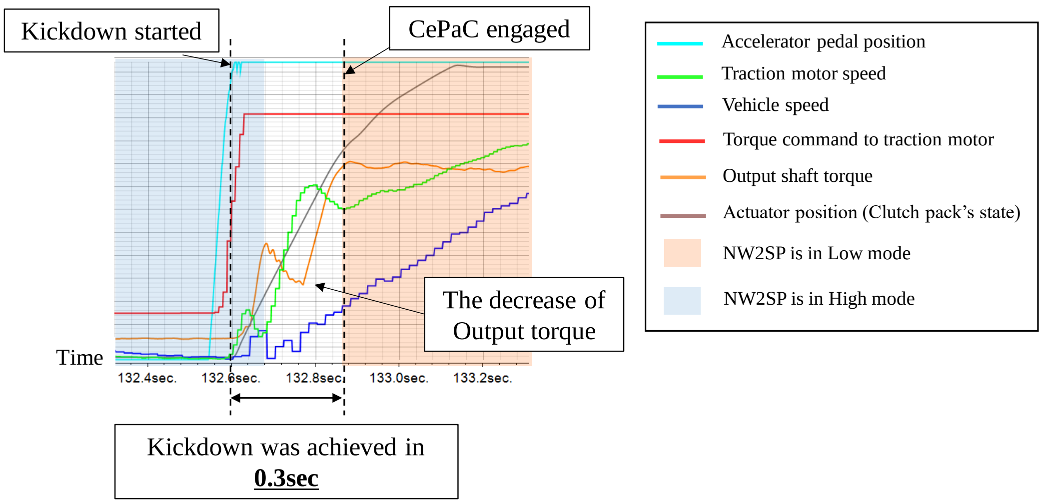


Fig. 8 Experiment result of Kickdown

the High mode is used for the regeneration. The hard acceleration is then requested, Kick-down function is prepared under 60 km/h. Upshifting and Kickdown were evaluated based on the subjective judgement by the passengers and the output shaft torque. Output torque was measured from torque sensors (FGDH-3A, Tokyo Measuring Instruments Laboratory Co., Ltd.) mounted on the left and right drive shafts. The validation vehicle tests were conducted in a linear cruse over a flat road.

5.4 Test result

Figure 7 show two upshifting test results. Figure 7 (a) shows a result by the step control for the traction motor control during shifting. In the torque phase, a sharp increase of output torque appears. And in the inertia phase, a long vibration of output torque called Clutch Judder appears for around 1.3 seconds. The driver felt an uncomfortable vibration during gear shifting situation. On the other hand, figure 7 (b) shows a result by the ramp control and the torque reduction is applied to the traction motor during the shifting. The ramp torque control is applied in the torque phase. The torque reduction is applied in the inertia phase until the traction motor speed and the vehicle speed are agreed with. As the results, the sharp increase of output torque in the torque phase is disappeared and the clutch judder is not existed after 0.3 seconds. The driver felt no shock during shifting.

Figure 8 shows an evaluation result of Kickdown from 40 km/h in a linear cruse over a flat road. Kickdown is completed within 0.3 seconds after strong acceleration. The eCuPa was opened at around 132.7 sec. (orange line drops), the CePaC was engaged at around 132.75 sec. (orange line increases). The passenger felt a hesitation moment of kickdown by 0.1 sec between the eCuPa is opened and the CePaC is engaged. To decrease the hesitation moment of kickdown is a future challenge.

6. CONCLUSION

In this paper, we propose the structure and the control method of a simple two speed transmission using CePaC (Centrifugal Pawl Clutch) and eCuPa (e-Clutch Pack) controlled with an actuator. We verified the one-way clutch function enables smooth gear shifting with the simple actuator control and the traction motor torque control. Upshifting with the traction motor torque reduction achieves the smooth seamless shifting by 0.3 seconds. Kickdown shifting can be completed within 0.3 seconds by only the traction motor torque control in proportion to the accelerator pedal. However, the moment hesitation of traction motor is felt.

The following are some of the future directions for these experiments:

(1) To develop the motor and the transmission control that can achieve the seamless shifting in various conditions.

(2) To confirm the output torques comparing between the down-sizing motor with two speed transmission concept and a motor with fixed reduction gear.

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