770 *Journal of Mechanical Science and Technology (KSME Int. J.), Vol. 20, No. 6, pp. 770~781, 2006*

Design and Performance Verification of Compound CVTs with 2K-H I type Differential Gear

Yeon-Su Kim*
Small Transit Research Team, Korea Railroad Research Institute,
#360-1 Woram-dong, Uiwang-si Gyeonggi-do 437-757, Korea
Jae-Min Park
School of Mechanical Engineering, Gangwon Human Resources Development Institute,
#165-1, Junghwage-ri, Bukbang-myeon, Hongchun-gun, Gangwon-do, 250-885, Korea
Sang-Hoon Choi
School of Mechanical and Aerospace Engineering, Konkuk University,
#1 Hwayang-Dong, Gwangjin-Gu, Seoul-City 437-757, Korea

This paper defined design constraints for the compound CVTs (continuously variable transmissions) by combining power-circulation-mode CVTs and power-split-mode CVTs, which were proposed for connecting 2K-H I-type differential gear to V-belt-type CVU (Continuously Variable Unit). The design constraints are the necessary and sufficient conditions to avoid geometrical interferences among elements in the compound CVTs, and to guarantee smooth assembly between the power-circulation-mode CVT and power-split-mode CVT. Two compound CVTs were designed and manufactured in accordance with the design constraints. With these compound CVTs, theoretical analysis and performance experiments were conducted. The results showed that the design constraints were valid and effective design method, and that the designed compound CVTs had the improved performance.

Key Words: Compound CVT (Continuously Variable Transmission), Differential Gear, Power-Circulation Mode, Power-Split Mode, Design Constraints

1. Introduction

The CVT, with its excellent power transmission performance and reduced fuel consumption, can change its speed ratio continuously and can control its engine speed and vehicle speed independently at the automobile application. Although many types of CVUs are available, almost all of them do not have a geared neutral function, are less efficient, and have shorter lifetimes compared to conventional gear transmissions (Beachley and Frank, 1980).

To overcome the problems associated with the use of CVUs, there are ongoing researches on new types of CVTs employing a combination of conventional CVUs and differential gears. CVTs with combined CVUs and differential gears are classified into the power split mode and the power circulation mode, which have opposite features. That is, the power split mode has a compact design, enhanced efficiency, a longer lifetime, and an extended transmission range. It cannot realize, however, the geared neutral and reverse motion functions by itself. On the other hand, the power circulation mode has geared neutral, reverse motion, and forward motion functions, but has lower efficiency. In addition, it does not have a compact design, and it has a shorter lifetime due to the

---

* Corresponding Author,
E-mail : yskim@krri.re.kr
TEL : +82-31-460-5730; **FAX** : +82-31-460-5749
Small Transit Research Team, Korea Railroad Research Institute, #360-1 Woram-dong, Uiwang-si Gyeonggi-do 437-757, Korea. (Manuscript **Received** September 28, 2005; **Revised** March 22, 2006)

high power transmission ratio of its components (Macmillan and Davis, 1965 ; White, 1967 ; Yu and Beachley, 1985 ; Wohl et al., 1993 ; Mucino and Smith, 1994 ; Morozumi and Kishi, 1997). Kim and Choi (2000, 2002 and 2004) have proposed some designs of power-circulation-mode CVTs and power-split-mode CVTs, by connecting the V-belt-type CVU with 2K-H I-, 2K-H II-, and K-H-V-type differential gears. In addition, the authors have developed theoretical formulas to determine the efficiency, power flow, and power transmission ratio of CVUs, the power transmission ratio of differential gears, and the speed ratios of power-circulation-mode CVTs and power-split-mode CVTs (Kim and Choi, 2000, 2002 ; Choi and Kim, 2000 ; Choi, 2003).

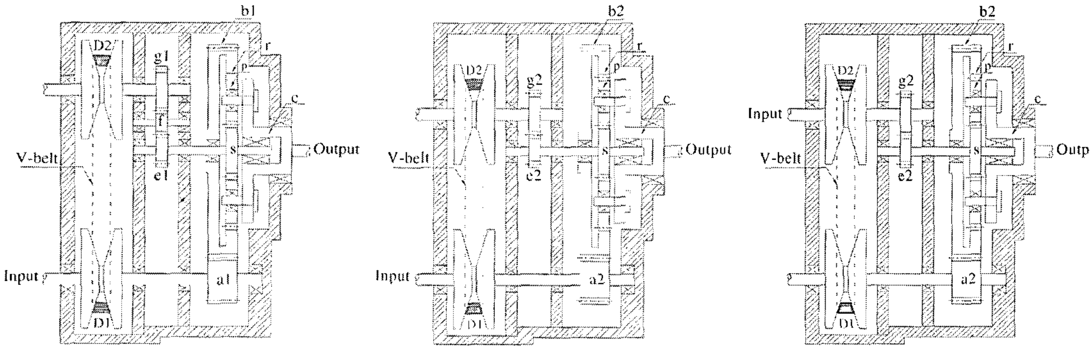
There are many ongoing studies of compound CVTs that show how their performance can be improved by combining power-circulation-mode CVTs and power-split-mode CVTs. Almost all compound CVTs, however, should be equipped with an additional chain drive or should utilize several CVUs at the same time (Roberts, 1984 ; Macey, 1986 ; Hanachi, 1990 ; Morozumi et al., 1992 ; Kishi et al., 1992). Kim and Choi recently proposed some compound CVT mechanisms that combine one V-belt-type CVU with one differential gear, on the basis of some research results (Kim and Choi, 2000 ; Choi and Kim, 2000), but without an additional chain drive or CVU (Kim and Choi, 2002a, 2002b ; Choi, 2003 ; Park et al., 2004).

This paper defined design constraints for the compound CVTs (continuously variable transmissions) by combining power-circulation-mode CVTs and power-split-mode CVTs, which were proposed for connecting 2K-H I-type differential gear to V-belt-type CVU (Continuously Variable Unit). The design constraints are the necessary and sufficient conditions to avoid geometrical interferences among elements in the compound CVTs, and to guarantee smooth assembly between the power-circulation-mode CVT and power-split-mode CVT. Two compound CVTs were designed and manufactured in accordance with the design constraints. Meanwhile, the authors verified the validity of the design constraints, and performance enhancement of the designed compound CVTs through theoretical analysis and performance experiments.

2. Basic Configurations

This study describes the design of two types of compound CVTs using three basic-configuration CVTs, by connecting V-belt-type CVU and 2K-H I-type differential gear, as shown in Fig. 1. Although the basic configurations of power-circulation-mode CVT and power-split-mode CVTs have the same structure, their power flows differ depending on whether or not they have an idle gear (f).

Tables 1 and 2 show the theoretical design equations for determining the power flow mode, speed ratio (i), efficiency (η), and power transmission ratio (P_{CVU}/P_I) of the CVU for the input



(a) Power circulation mode 1 (b) Power split mode 1 (c) Power split mode 2

Fig. 1 Basic configurations for design of the compound CVTs

Table 1 Theoretical design equations for the power-circulation-mode CVT

configuration	differential gear ratio (i_0)	equivalent relation (i_{eq})	speed ratio (i)	overall efficiency of the CVT (η)	power transmission ratio of the CVU (P_{CVU}/P_i)	power transmission ratio of the differential gear (P_{dif}/P_i)
power circulation mode I	$\frac{z_r}{z_s}$	$\frac{D_1 z_{g1} z_{b1}}{D_2 z_{e1} z_{a1}}$	$\frac{i_{eq}-i_0}{1+i_0}\frac{z_{b1}}{z_{a1}}$	$\frac{\eta_0'(1+\eta_0 i_0)(i_{eq}-i_0)}{(1+i_0)(i_0-\eta_0\eta_0' i_0)}$	$\frac{\eta_0' i_{eq}}{i_{eq}-\eta_0\eta_0' i_0}$	$\frac{\eta_0\eta_0' i_0}{i_{eq}-\eta_0\eta_0' i_0}$
			$-\frac{i_0-i_{eq}}{1+i_0}\frac{z_{a1}}{z_{b1}}$	$\frac{(\eta_0+i_0)(i_0-i_{eq})}{(1+i_0)(i_0-\eta_0\eta_0' i_{eq})}$	$\frac{\eta_0 i_{eq}}{i_0-\eta_0\eta_0' i_{eq}}$	$\frac{i_0}{i_0-\eta_0\eta_0' i_{eq}}$

Table 2 Theoretical design equations for the power-split-mode CVTs

configuration	differential gear ratio (i_0)	equivalent relation (i_{eq})	speed ratio (i)	overall efficiency of the CVT (η)	power transmission ratio of the CVU (P_{CVU}/P_i)	power transmission ratio of the differential gear (P_{dif}/P_i)
power split mode 1	$\frac{z_r}{z_s}$	$\frac{D_1 z_{g2} z_{b2}}{D_2 z_{e2} z_{a2}}$	$-\frac{i_0+i_{eq}}{(1+i_0)}\frac{z_{a2}}{z_{b2}}$	$\frac{\eta_0'(\eta_0+i_0)(1+\eta_0 i_0)(i_0+i_{eq})}{(1+i_0)\{i_0(1+\eta_0 i_0)i_0\eta_0'+(\eta_0+i_0)i_{eq}\}}$	$\frac{\eta_0' i_{eq}(\eta_0+i_0)}{\{(1+\eta_0 i_0)i_0\eta_0'+(\eta_0+i_0)i_{eq}\}}$	$\frac{\eta_0' i_0(1+\eta_0 i_0)}{\{(1+\eta_0 i_0)i_0\eta_0'+(\eta_0+i_0)i_{eq}\}}$
power split mode 2			$-\frac{i_{eq}+i_0}{i_{eq}(1+i_0)}\frac{z_{g2}}{z_{e2}}$	$\frac{\eta_0'(\eta_0+i_0)(1+\eta_0 i_0)(i_{eq}+i_0)}{(1+i_0)\{i_0(1+\eta_0 i_0)+i_{eq}\eta_0'(\eta_0-i_0)\}}$	$\frac{\eta_0' i_0(1+\eta_0 i_0)}{\{i_0(1+\eta_0 i_0)+i_{eq}\eta_0'(\eta_0+i_0)\}}$	$\frac{\eta_0' i_{eq}(\eta_0+i_0)}{\{i_0(1+\eta_0 i_0)+i_{eq}\eta_0'(\eta_0+i_0)\}}$

power (P_i), and the power transmission ratio (P_{dif}/P_i) of the differential gear for the input power (P_i) of the basic configurations shown in Fig. 1. In the equations, D_1 and D_2 are the effective diameters of the two variable pulleys. z_{a1}, z_{b1}, z_{e1}, z_{g1}, z_{a2}, z_{b2}, z_{e2}, z_{g2} and z_f are the numbers of teeth of gears a1, b1, e1, g1, a2, b2, e2, g2 and f, respectively. η_0' is derived by multiplying the efficiency of the CVU by the efficiency of various gear trains. To calculate η_0', the authors used Eq. (1) for the basic configuration that has an idle gear (f), as shown in Fig. 1(a), and Eq. (2) for the basic configurations that have no idle gear (f), as shown in Figs. 1(b) and (c), respectively. In Eq. (1), η_{CVU} refers to the efficiency of the V-belt-type CVU ; η_{a1b1}, to the efficiency between gear a1 and gear b1 ; η_{e1f}, to the efficiency between gear e1 and gear f; and η_{fg1}, to the efficiency between gear f and gear g1. In Eq. (2), η_{a2b2} represents the efficiency between gear a2 and gear b2 ; and η_{e2g2}, the efficiency between gear e2 and gear g2 (Kim and Choi, 2000 ; Choi and Kim, 2000).

$$\eta_0' = \eta_{a1b1}\eta_{e1f}\eta_{fg1}\eta_{CVU} \tag{1}$$

$$\eta_0' = \eta_{a2b2}\eta_{e2g2}\eta_{CVU} \tag{2}$$

3. Design of Compound CVTs

3.1 V-belt-type CVU

In the V-belt-type CVU, two variable pulleys were installed at two shafts that had fixed center distances, and were operated by the rubber V-belt, as shown in Fig. 2. If the radius of gyration of one of the variable pulleys was changed through the mechanical link connected to the speed ratio controller, the radius of gyration of the other pulley would have been automatically adjusted by the coil spring and the speed ratio would have changed continuously. The authors designed the V-belt-type CVU to have an overall speed ratio

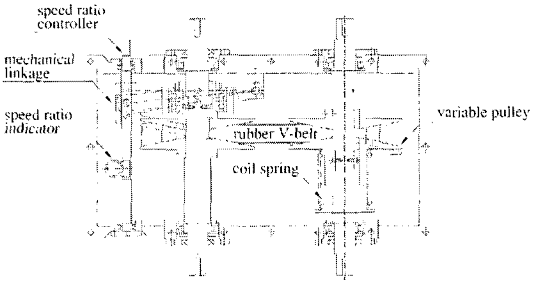


Fig. 2 Drawing of the V-belt-type CVU

range of 0.5 to 2.0, a center distance of 279 mm, and two variable pulleys with a maximum diameter of 216 mm. For the rubber V-belt, the authors chose a US Standard (RMA/MPTA 2322V 421) product that had a tooth-shaped inner side so that it could endure the axial force on the side of the belt. The rubber V-belt had a width of 36.5 mm, a belt wedge angle of 22°, and a belt pitch length of 1069.3 mm.

3.2 2K-H I-type Differential Gear

The 2K-H I-type differential gear consists of the sun gear (s), the ring gear (internal gear, r), and three planet gears (p) connected by a carrier (c) that guides the smooth revolution of the planet gears, as shown in Fig. 3. All the constituent gears used were standard spur gears to provide a pressure angle of 20°, a module of 2.0, and a teeth width of 30 mm. The number of teeth of the sun gear, the ring gear and the planet gears were $z_s=24$, $z_r=72$, and $z_p=24$, respectively. Assuming that the carrier was fixed, the basic efficiency (η_0) of the 2K-H I-type differential gear was calculated by multiplying the efficiency (η_{sp}) between the sun gear (s) and the planet gears (p), and the efficiency (η_{rp}) between the ring gear (r) and the planet gears (p) (Kim et al., 2000; Morozumi, 1989).

$$\eta_0=\eta_{sp}\eta_{rp} \tag{3}$$

3.3 Design requirements

Because compound CVTs are designed as combinations of power-circulation-mode CVTs and power-split-mode CVTs, they should have reverse motion, geared neutral, underdrive, and overdrive functions. In addition, they should perform with improved efficiency and a reduced power transmission ratio compared to power-circulation-mode CVTs. Fig. 4 shows the concept for the design requirements of compound CVTs (Choi, 2003; Kim and Choi, 2002a; Kim and Choi, 2002b). In this paper, the authors designed the two compound CVTs in such a manner as to comply with the following design requirements:

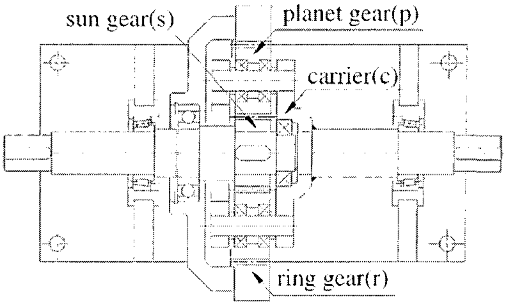


Fig. 3 Drawing of the 2K-H I-type differential gear

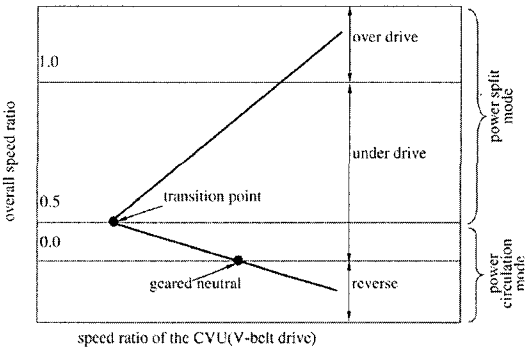


Fig. 4 Power flow modes and speed ratio range of the compound CVTs

(1) The power-circulation-mode and the power-split-mode CVTs should have opposite speed ratio gradients based on their transition point.

(2) The power-circulation-mode and the power-split-mode should have the same speed ratio at the transition point of the power flow. The authors designated the speed ratio at the transition point as 0.5, corresponding to the first gear of the automobile gear transmission.

(3) The power-circulation-mode CVT should have reverse motion and geared neutral functions, and the power-split-mode CVT should have speed ratios above 1.0 so that the compound CVTs can have reverse motion, geared neutral, underdrive, and overdrive functions within the overall speed ratio range.

3.4 Design constraints

This paper has defined design constraints for compound CVTs which were proposed by connecting 2K-H-I-type differential gear to V-belt-type CVU. The design constraints are the necessary and sufficient conditions to avoid geometrical interferences among elements in the compound CVTs, and to guarantee smooth assembly between

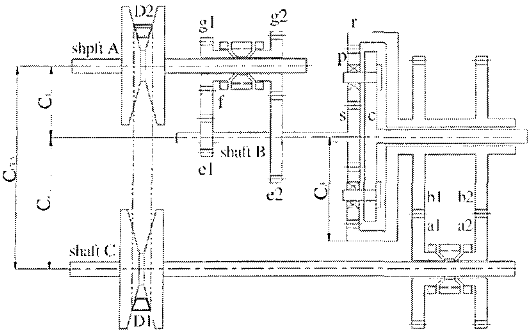


Fig. 5 Design constraints of the compound CVTs

the power-circulation-mode CVT and power-split-mode CVT. Fig. 5 shows the concept of the design constraints for the compound CVTs. In this paper, the authors designed the two compound CVTs in such a manner as to comply with the following design constraints:

(1) The differential gear should have no interference with the shaft of the variable pulley (D_1). In other word, the center distance (C_2) between shaft B and C should be larger than the radius (C_3) of the differential gear. Therefore, Eq. (4) should be sufficient in the design of the compound CVTs.

$$C_2 > C_3 \tag{4}$$

(2) The center distance between gear e1 and gear g1 should be identical with the center distance between gear e2 and gear g2. In the case of gears a1, b1, a2 and b2, the same design constraint should be applied. Therefore, Eqs. (5) and (6) should be sufficient in the design of the compound CVTs

$$C_1 = z_{g1} + z_{e1} + 2z_f = z_{g2} + z_{e2} \tag{5}$$

$$C_2 = z_{b1} + z_{a1} = z_{b2} + z_{b2} \tag{6}$$

(3) The center distance of the V-belt-type CVU should be identical with the sum of the center distance between gear e1 (or e2) and gear g1 (or g2) and the center distance between a1 (or a2) and b1 (or b2).

$$C_{CVU} = C_1 + C_2 \tag{7}$$

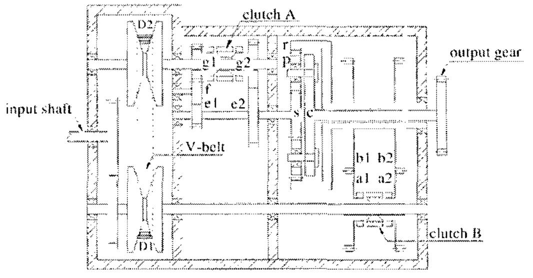


Fig. 6(a) Compound CVT A-11 composed of power circulation mode 1 and power split mode 1

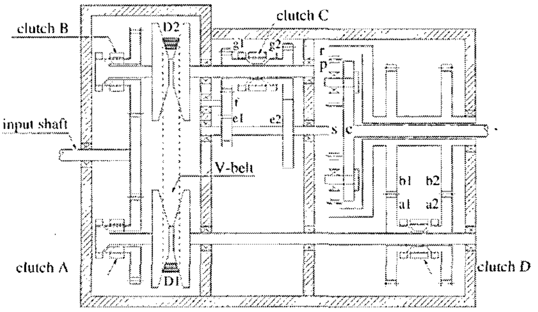


Fig. 6(b) Compound CVT A-12 composed of power circulation mode 1 and power split mode 2

3.5 Designed compound CVTs

Figure 6(a) shows the structure of the compound CVT A-11, designed by combining the power-circulation-mode-1 CVT in the basic configurations (Fig. 1(a)) and the power-split-mode-1 CVT (Fig. 1(b)). Fig. 6(b) shows the structure of the compound CVT A-12, designed by combining the power-circulation-mode-1 CVT (Fig. 1(a)) and the power-split-mode-2 CVT (Fig. 1 (c)). In the compound CVT A-11, the power circulation mode was achieved when both the A and B clutches were moved to the left, and the power split mode was achieved when both the A and B clutches were moved to the right. In the compound CVT A-12, the power circulation mode was achieved when the A, C and B clutches were moved to the left and the B clutch was moved to the right, and the power split mode was achieved when all the clutches were moved to the directions opposite that of the power circulation mode (Kim and Choi, 2002a).

Based on the proposed compound CVT mechanisms, design equations, design requirements and design constraints, the authors designed two compound CVTs. All the numbers of teeth of the

Table 3 Numbers of teeth of gear trains

Designed compound CVTs		Numbers of teeth
A-11	Power circulation mode 1	$z_{e1}=41$, $z_{g1}=82$, $z_f=18$, $z_{a1}=60$, $z_{b1}=60$
	Power split mode 1	$z_{e2}=53$, $z_{g2}=106$, $z_{a2}=30$, $z_{b2}=90$
A-12	Power circulation mode 1	$z_{e1}=41$, $z_{g1}=82$, $z_f=18$, $z_{a1}=60$, $z_{b1}=60$
	Power split mode 2	$z_{e2}=77$, $z_{g2}=77$, $z_{a2}=50$, $z_{b2}=75$

gears in the power' circulation mode were designed to be identical in A-11 and A-12. Table 3 shows the numbers of teeth of the gears in the A-11 and A-12 designed compound CVTs.

4. Performance Verification of Compound CVTs

4.1 Theoretical analysis

To analyze the efficiency of the gear trains in the designed compound CVTs, the authors considered only the friction loss (the friction coefficient 0.1) at the gear's teeth surface (flank), without applying the bearing loss and the lubricant churning loss (Kim et al., 2000; Morozumi, 1989). The authors used the efficiency of all standard spur gear trains, 0.982, based on the studies. Then they measured the efficiency of the V-belt-type CVU at various speed ratios by changing the CVU's input shaft revolution speed using an experimental rig, and calculated the efficiency of the V-belt-type CVU using linear interpolation, based on the experimental results. Fig. 7 shows the measured efficiencies of the manufactured V-belt-type CVU needed for the performance analysis of the designed compound CVTs.

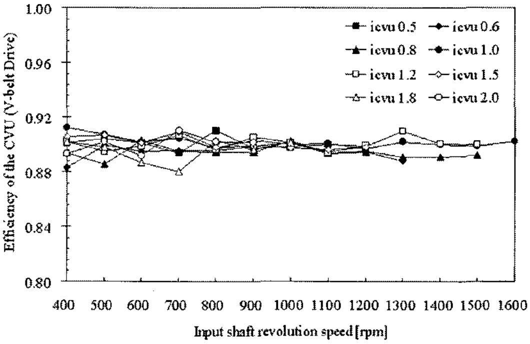


Fig. 7 Experimental results for efficiencies of the V-belt-type CVU as changing speed ratios and input shaft revolution speed

The authors analyzed the efficiencies, speed ratios, and power transmission ratios (P_{dif}/P_i) of the differential gear to the input power (P_i), and the power transmission ratios (P_{CVU}/P_i) of the CVU to the input power (P_i) for the compound CVT A-11, as shown in Fig. 6(a), and for the compound CVT A-12, as shown in Fig. 6(b), using Tables 1-3.

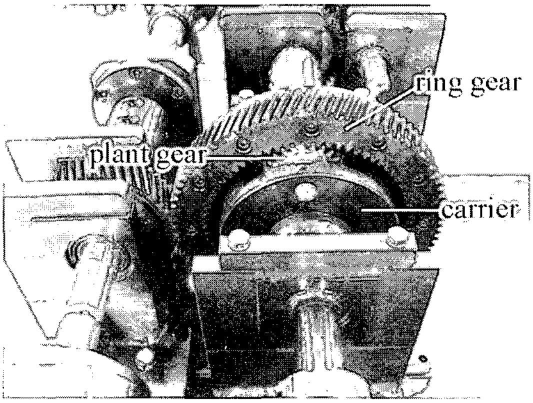


Fig. 8 Photograph of the 2K-H I-type differential gear

4.2 Performance experiment

4.2.1 Manufacture of the compound CVTs

The V-belt-type CVU and the 2K-H I-type differential gear designed as shown in Figs. 2 and 3 were manufactured as shown in Figs. 8 and 9, to be installed in both the A-11 and A-12 compound CVTs.

4.2.2 Experimental rig

The experiments to determine the performance of the compound CVTs were carried out with an experiment rig that consisted of an 11-kW AC motor, the V-belt-type CVU, the 2K-H I-type

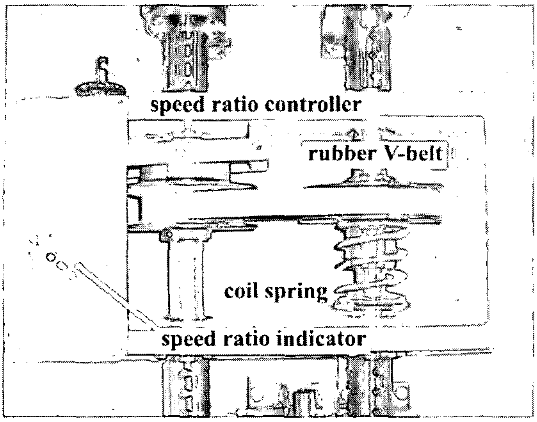


Fig. 9 Photograph of the V-belt-type CVU

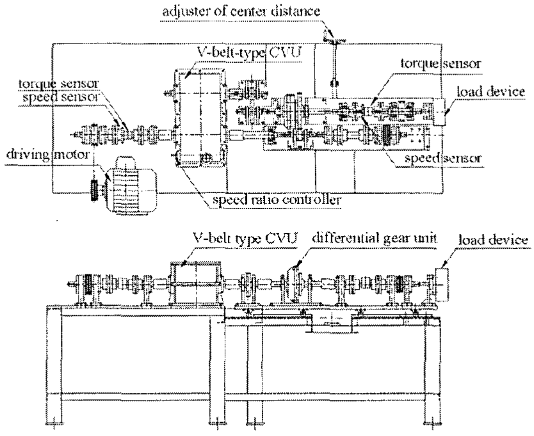


Fig. 10(a) Schematic drawing of the experimental rig for compound CVTs

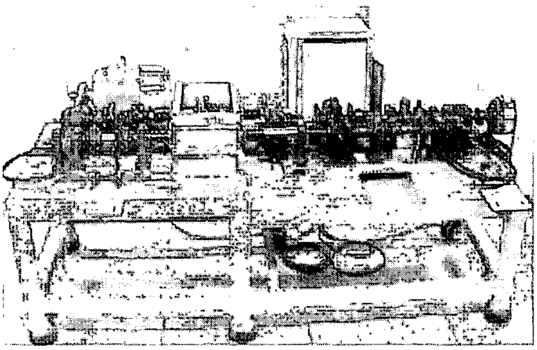


Fig. 10(b) Photograph of the experimental rig for compound CVTs

differential gear, torque sensors, speed sensors, a load device, and various gear trains, as shown in Fig. 10. The speed of the AC motor was controlled so that it could keep the preset speed constant regardless of the load application. The authors installed two torque sensors and two speed sensors at both the input shaft and the output shaft of the experimental rig to measure the torques and speeds. A strain-gauge-type sensor was used as the torque sensor, with a measuring range of 0–100 Nm. An optical fiber sensor with a red LED light source was used as the speed sensor, with a measuring range of 60-2,400 rpm. An electromagnetic particle brake with a capacity of 0-100 Nm was used as the load device, and it was able to continuously control the load magnitude. Idle operations were undertaken for 20 minutes under all conditions for the performance experiment to stabilize the tension on the rubber V-belt, to stabilize the friction on the teeth surfaces of the gear trains, and to cool down the load device.

4.2.3 Analysis of the experimental results

The authors operated the compound CVTs using the experimental rig, as shown in Fig. 10, and applied the load to their output shaft. Then they measured the revolution speeds and the torques at both the input shaft and the output shaft. They experimented on the efficiencies and speed ratios of the power-circulation-mode CVT and the power-split-mode CVTs as changing revolution speed of the input shaft, and used Eq. (8) to calculate the efficiencies and speed ratios of the compound CVTs. In the formula, η refers to the efficiency of the compound CVTs ; i, to their speed ratio ; T_I, to the torque occurring at the input shaft ; T_O, to the torque occurring at the output shaft ; ω_I, to the revolution speed of the input shaft ; and ω_O, to the revolution speed of the output shaft (SAE Recommended Practice, 1994).

$$\eta=\frac{T_O\omega_O}{T_i\omega_i}=\frac{T_O}{T_i}i \qquad (8)$$

5. Results and Discussions

5.1 Compound CVT A-11

Figure 11(a) shows the results of the performance experiment carried out with a 0.5 speed ratio for the V-belt-type CVU and with the power split mode 1 of the compound CVT A-11. When the

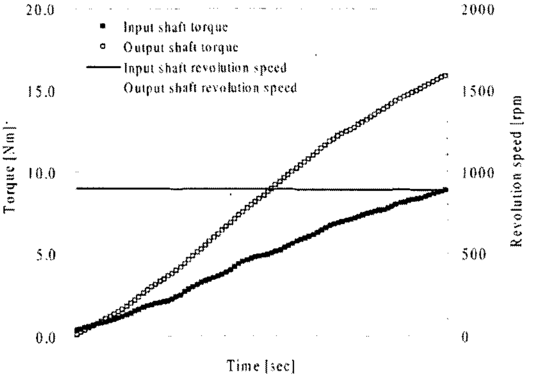


Fig. 11(a) Experimental results for the power split mode 1 of the compound CVT A-11 at iCVU=0.5, 900 rpm of input shaft

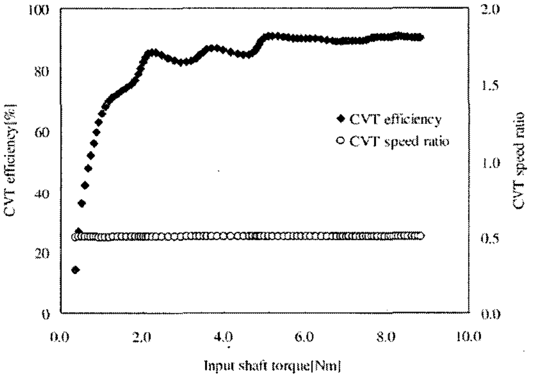


Fig. 11(b) Experimental efficiencies and speed ratios for the power split mode 1 of the compound CVT A-11 at iCVU=0.5, 900 rpm of input shaft

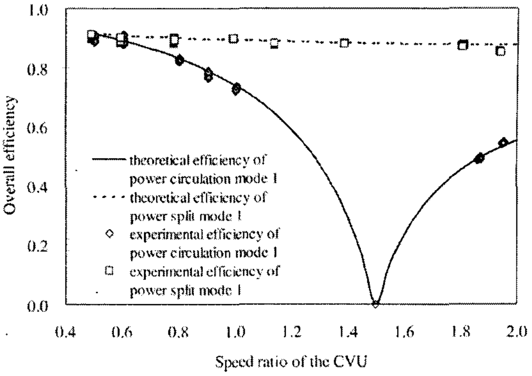


Fig. 12(a) Experimental and theoretical efficiencies of the compound CVT A-11 at 1,200 rpm of input shaft

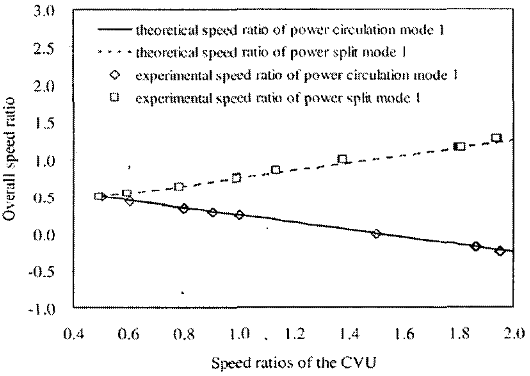


Fig. 12(b) Experimental and theoretical speed ratios of the compound CVT A-11 at 1,200 rpm of input shaft

load was increased, the torques at the input shaft and the output shaft increased but the revolution speed of each shaft remained constant. Fig. 11(b) shows the efficiency and speed ratios calculated by substituting the experiment results in Eq. (8), as shown in Fig. 11(a). The efficiency increased up to the maximum value and the speed ratio remained constant as the torque increased (as the load increased).

Figures 12(a) and (b) show the comparison of the results of the theoretical analysis and the performance experiment for the efficiencies and speed ratios of the compound CVT A-11, respectively, at 1,200 rpm of the input shaft. The efficiencies that resulted from the theoretical analysis and the performance experiment were similar–i.e., below the 5% P difference range. This difference might have come from the inertial effects of the compound CVT and the experiment rig, which were not considered in the theoretical analysis, and from the losses in the connection parts and bearings. The theoretical analysis and the performance experiment, however, had almost the same results for the speed ratios, the occurrence of the geared neutral function, and the transition point between the power circulation mode 1 and the power split mode 1.

Figures 13(a) and (b) show the results of the performance experiment for the efficiencies and speed ratios of the compound CVT A-11 at various input shaft revolution speeds. In the power circulation mode 1 and the power split mode 1, the efficiencies and speed ratios were almost con-

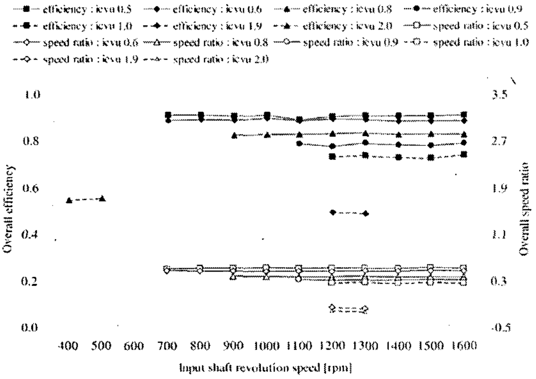


Fig. 13(a) Experimental efficiencies and speed ratios for power circulation mode 1 of the compound CVT A-11 at various input shaft revolution speed

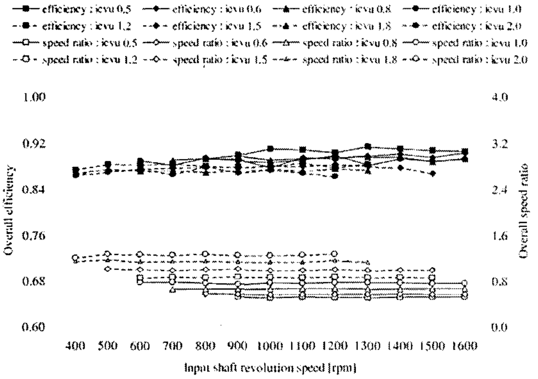


Fig. 13(b) Experimental efficiencies and speed ratios for power split mode 1 of the compound CVT A-11 at various input shaft revolution speed

stantly maintained regardless of the variations in the input shaft revolution speed (from 400 rpm to 1,400 rpm). They were similar to the results of the theoretical analysis.

Figure 14 shows the results of the theoretical analysis of the power transmission ratio (P_{CVU}/P_i) of the V-belt-type CVU to the input power (P_i), and of the power transmission ratio (P_{dif}/P_i) of the differential gear to the input power (P_i) for the compound CVT A-11. In the case of the power split mode 1, the power transmission ratios of the V-belt-type CVU and the differential gear were lower than 1.0, because they split up to transmit the overall input power at an assigned ratio with respect to each other. In the case of the power circulation mode 1, however, the power transmission ratios of the V-belt-type CVU and the differential gear were higher because part of the output power was re-circulated back to the inside of the CVT. In particular, because all the output power was re-circulated back to the inside of the CVT at the geared neutral, each power transmission ratio was at its maximum value.

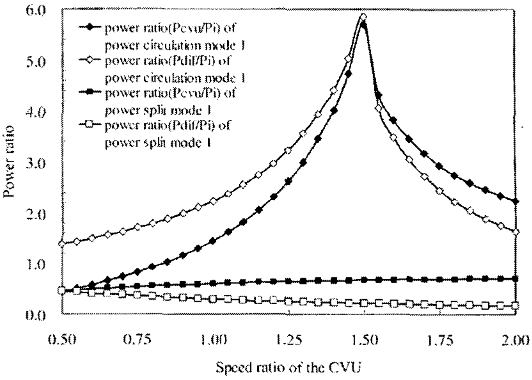


Fig. 14 Power transmission ratios of constituents in the compound CVT A-11

5.2 Compound CVT A-12

Figures 15(a) and (b) compare the results of the theoretical analysis and the performance experiment for the efficiencies and speed ratios of the compound CVT A-12, respectively, at 1,200 rpm of the input shaft. As the compound CVT A-11, the resulting efficiencies in the theoretical analysis and the performance experiment were similar, at an difference range of below 5% P. Moreover, the theoretical analysis and the performance experiment have almost the same results in terms of the speed ratios, the occurrence of geared neutral, and the transition point between the power circulation mode 1 and the power split mode 2.

Figure 16 shows the results of the performance experiment for the power split mode 2 of the compound CVT A-12 at various input shaft revolution speeds. As the compound CVT A-11, the efficiencies and speed ratios were almost constantly maintained regardless of the variations in the input shaft revolution speed (from 400 rpm to 1,400 rpm). They were also similar to the results

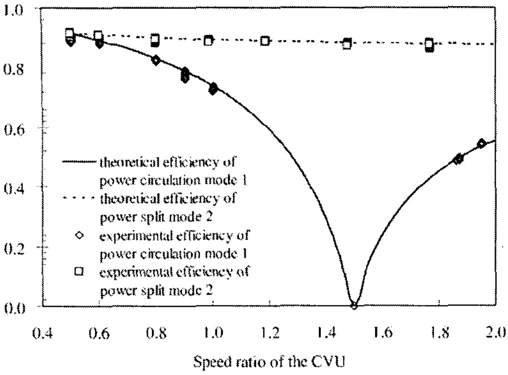


Fig. 15(a) Experimental and theoretical efficiencies of the compound CVT A-12 at 1,200 rpm of input shaft

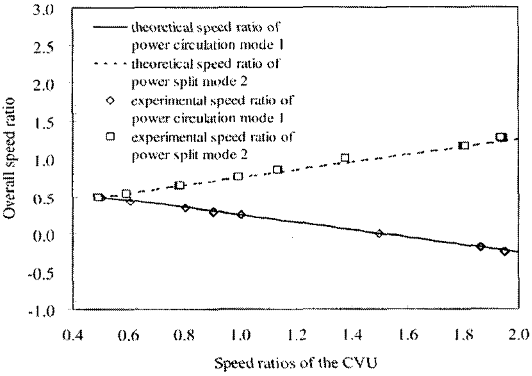


Fig. 15(b) Experimental and theoretical speed ratios of the compound CVT A-12 at 1,200 rpm of input shaft

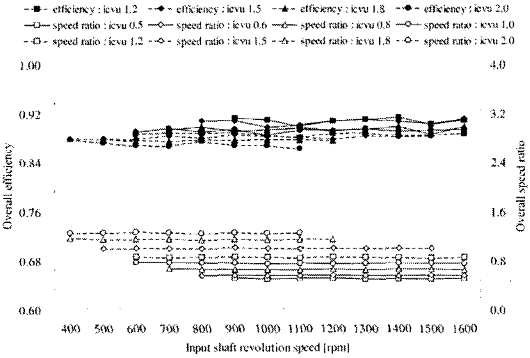


Fig. 16 Experimental efficiencies and speed ratios for power split mode 2 of the compound CVT A-12 at various input shaft speed

of the theoretical analysis. The results with respect to the power circulation mode 1 were identical with those in Fig. 13(a).

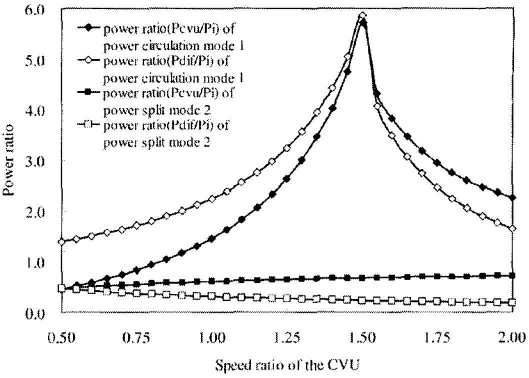


Fig. 17 Power transmission ratios of constituents in the compound CVT A-12

Figure 17 shows the results of the theoretical analysis with respect to the power transmission ratio (P_{CVU}/P_i) of the V-belt-type CVT to the input power (Pi), as well as the power transmission ratio (P_{dif}/P_i) of the differential gear to the input power (P_i) in the compound CVT A-12. As the compound CVT A-11, the compound CVT A-12 reduced the power transmission ratio of the components compared with the use of the power circulation mode alone.

5.3 Discussions

There were no any geometrical interferences among elements in the designed compound CVTs which had stable performances as changing revolution speed of the input shaft. It was also verified that the power-circulation-mode CVT and power-split-mode CVTs could be assembled smoothly. In the designed compound CVTs, which have no additional chain drive or CVU, the power circulation mode realized reverse motion, the geared neutral, and part of the underdrive functions ; whereas the power split mode, which has a high efficiency and the components of which have low power transmission ratios, almost fully realized the underdrive and overdrive functions. Accordingly, the compound CVTs were more efficient, had components with lower power transmission ratios, and had a more compact design than the power-circulation-mode CVT alone. In addition, the compound CVTs had the geared neutral and reverse motion functions compared to the power-split-mode CVT alone.

6. Conclusions

The authors defined design constraints for the compound CVTs by combining power-circulation-mode CVTs and power-split-mode CVTs, which were proposed for connecting 2K-H I-type differential gear to V-belt-type CVU. The authors also designed two compound CVTs in accordance with the design constraints. The authors deduced the following conclusions by carrying out theoretical analysis and performance experiments to derive the efficiencies, speed ratios, power flows, and power transmission ratios of the V-belt-type CVU and the 2K-H I-type differential gear for the designed compound CVTs.

(1) The design constraints were valid and effective design method for the compound CVTs, which have been proposed by connecting 2K-H I-type differential gear to V-belt-type CVU.

(2) The compound CVTs could realize stable performances as changing revolution speed of the input shaft, and improved performance compared to either the power-circulation-mode CVT or the power-split-mode CVT alone.

(3) The authors verified the validity of the design equations for the compound CVTs through various performance experiments.

References

Beachley, N. H. and Frank, A. A., 1980, "Principles and Definitions for Continuously Variable Transmissions with Emphasis on Automotive Application," ASME Paper 80-C2/DET-95.

Choi, S. H. and Kim, Y. S., 2000, "Characteristics on the Output Coupled CVT with Differential Gear," *Journal of the KSPE*, Vol. 18, No. 3, pp. 205~216.

Choi, S. H., 2003, "Performance of CVTs Composed of a Differential Gear Unit and a V-belt Drive," *Journal of the KSPE*, Vol. 20, No. 2, pp. 199~208.

Hanachi, S., 1990, "A Study of the Dynamics of a Split-Torque, Geared-Neutral Transmission Mechanism," *Journal of Mechanical Design*, Vol. 112, pp. 261~270.

Kim, Y. S., Choi, S. U. and Choi, S. H., 2000, "A Study on the Efficiency Analysis of 2K-H Type Planetary Gear Train," *Journal of the KSPE*, Vol. 17, No. 3, pp. 200~207.

Kim, Y. S. and Choi, S. H., 2000, "Power Flow and Efficiency of Input Coupled type CVT combined Differential Gear Unit," *Journal of the KSPE*, Vol. 17, No. 11, pp. 141~150.

Kim, Y. S. and Choi, S. H., 2002a, "Development of CVTs Composed of a 2K-H I Type Differential Gear Unit and a V-belt Drive," *Transactions of the KSME (A)*, Vol. 26, No. 6, pp. 1060~1068.

Kim, Y. S. and Choi, S. H., 2002b, "Continuously Variable Transmission Composed of a V-belt Drive and a 2K-H II type Differential Gear Unit," *Transactions of the KSME (A)*, Vol. 26, No. 8, pp. 1495~1505.

Kishi, S., Morozumi, M., Furukawa, Y., Misawa, H. and Miyata, H., 1992, "A Study of a Variable Speed Transmission with a Hypocycloid Type Differential Gearing," *Journal of Japan Automotive technology Association*, Vol. 23, No. 2, pp. 91~96.

Macey, J. P., 1986, "Geared-Neutral Continuously Variable Transmission," US Patent No. 4644820.

Macmillan, R. H. and Davies, P. B., 1965, "Analytical Study of Systems for Bifurcated Power Transmission," *Journal of Mechanical Engineering Science*, Vol. 7, No. 1, pp. 40~47.

Morozumi, M., 1989, "The Theory and Design Method for Planetary Gear Drive and Differential Gear Unit, " *Japan Daily Industrial Paper*, Tokyo, pp. 8~31.

Morozumi, M., Kishi, S., Furukawa, Y. and Misawa, H., 1992, "A Study of Variable Speed Transmission with Differential Gear," *Journal of Japan Automotive technology Association*, No. 46, pp. 45~49.

Morozumi, M. and Kishi, S., 1997, "A Mechanical Consideration on CVT with a Differential Gearing," *Mechanical Researches (Japanese)*, Vol. 49, No. 5, pp. 570~578.

Mucino, V. H. and Smith, J. E., 1994, "Parametric Modeling and Analysis of a Planetary Gear-CVT Mechanism," SAE Paper 940519.

Park, J. M., Kim, Y. S. and Choi, S. H., 2004, "Performance Analysis of CVTs with a 2K-H II Differential Gear," *Journal of the KSPE*, Vol. 21, No. 4, pp. 170~178.

Roberts, R. W., 1984, "Continuously Variable Transmission with Synchronous shift," US Patent No.4589303.

White, G., 1967, "Properties of Differential Transmission," *The Engineer*, pp. 105~111.

Wohl, R., Long, T., Mucino, V. H. and Smith, J. E., 1993, "A Model for a Planetary-CVT Mechanism: Analysis and Synthesis," SAE Paper 930065.

Yu, D. and Beachley, N., 1985, "On the Mechanical Efficiency of Differential Gearing," *ASME Journal of Mechanisms, Transmissions and Automation in Design*, Vol. 107, pp. 61~67.

SAE Recommended Practice, 1994, "Continuously Variable Transmission Test Code for Passenger Cars," SAE J1618 AUG94, pp. 29.35~29.40.