International Journal of the Korean Society of Precision Engineering Vol. 3, No. 3, July 2002.

Experimental and Parametric Study on the Output Coupled type Continuously Variable Transmission

Yeon-Su Kim[1], Jae-Min Park[2], and Sang-Hoon Choi[3]

[1] Korea Railroad Research Institute, Kyongki-Do, Korea,
[2] Graduate School of Konkuk University, Seoul, Korea,
[3] Department of Mechanical Design and Production Engineering, Konkuk University, Seoul, Korea

ABSTRACT

The continuously variable transmission (CVT) mechanism considered here is the output coupled type which combines the functions of a 2K-H I type differential gear unit and a V-belt type continuously variable unit (CVU). One shaft of the CVU is connected directly to the output shaft and another shaft of it is linked to the differential gear unit. It is shown that some fundamental relations (speed ratios, power flows and efficiencies) for twelve mechanisms previously described are valid by various experimental studies, six of them produce a power circulation and the others produce a power split. Parametric analysis is carried out in relation to the efficiency, speed ratio and power ratios in order to assist in the design of an optimum configuration. Some useful properties associated with power flow modes also are discussed in the output coupled type continuously variable transmission.

Key Words : Continuously variable transmission, Output coupled type, Power circulation mode, Power split mode

Nomenclature

z = number of gear teeth
i_0 = gear ratio between an inner ring gear and a sun gear (z_r/z_s)
η_0 = basic efficiency of a differential gear unit
η_0' = efficiency between a CVU and gear trains except a differential gear unit
η = overall efficiency of a CVT mechanism
i = overall speed ratio of a CVT mechanism
Subscripts
r : inner ring gear, s : sun gear, c : carrier,
p : planet gear, b : outer ring gear, h : gear h
f : idler gear, e : gear e, g : gear g, a : gear a

1. Introduction

A continuously variable transmission mechanism composed of a 2K-H I type differential gear unit and a V-belt type continuously variable unit makes it possible for various configuration because a V-belt drive has two shafts and a 2K-H I type differential gear unit has three shafts. This mechanism has two basic configurations, input coupled type and output coupled type, as the location of a CVU. Futhermore, it has many advantages which are the decrease of size and weight, the increase of overall efficiency, the extension of speed ratio range and the generation of geared neutral.

There are many previous contributions related to this mechanism. An investigation on the overall efficiency have been executed[1,2]. Some relations associated with speed range, proportion of input power carried by a CVU, and mean value of power carried by a CVU had been derived[3]. Analytical methods for the efficiency analysis of the mechanism have been suggested[4]. However, these are not in agreement with the experimental results or not verified by experiment, or do not present quantitative criteria of power flow in this mechanism[1-4]. Some configurations related to this mechanism have been developed, theoretical analysis and experimental studies have been executed[5,6] or only theoretical analysis have been performed[7-9]. Authors have developed twelve configurations for the input coupled type CVT composed of a 2K-H I type differential gear unit and a V-belt type CVU with a variable-diameter pulley. The theoretical relations associated with efficiency, power flow and speed ratio have been derived, and proven by experimental studies[10,11]. More recently authors have also developed twelve configurations and theoretical relations for the output coupled type CVT, and some experimental study has been performed[12].

In this paper theoretical relations associated with efficiency and speed ratio for the twelve output coupled type CVT mechanisms developed are investigated through experimental studies, where six of them have a power circulation mode and the others have a power split mode. From the comparisons between theoretical and experimental results, it is shown that theoretical relations are valid. A parametric approach is to perform parametric sensitivity analysis, and is made based on the three independent parameters which are differential gear ratio (zr/zs), gear ratio zb/za and zg/ze.

2. General definitions

2.1 Continuously variable unit

The continuously variable unit considered in this paper is the V-belt drive with pulleys whose diameters may be varied, which is shown in Fig. 1. It has two variable-diameter pulleys with a fixed center distance, one pulley having its effective diameter set by a mechanical linkage, and the other one spring-loaded to provide automatic correspondence.

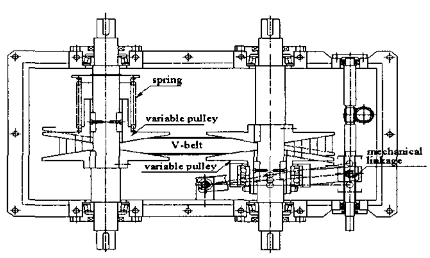


Fig. 1 V-belt type CVU with two variable pulleys

2.2 Differential gear unit

The 2K-H I type differential gear unit is shown in Fig. 2, which is composed of an inner ring gear, an outer ring gear, a sun gear, three planet gears and a carrier. The shafts of a ring gear, a sun gear and a carrier are called basic shafts which are concentric.

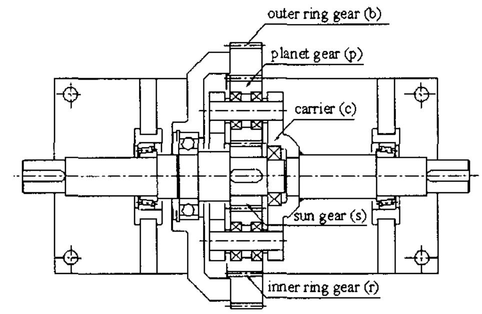


Fig. 2 2K-H I type differential gear unit

In case that a carrier is fixed, the efficiency of a differential gear unit is defined as a basic efficiency. It is the meshing efficiency between an inner ring gear and a planet gear (η_{rp}) times the meshing efficiency between a sun gear and a planet gear (η_{sp}).

$$\eta_0 = \eta_{rp}\eta_{sp} \tag{1}$$

2.3 Output coupled type CVT

In output coupled type CVT mechanism, a CVU is coupled directly to the differential gear unit and the remaining shaft of it is linked to the output shaft[3].

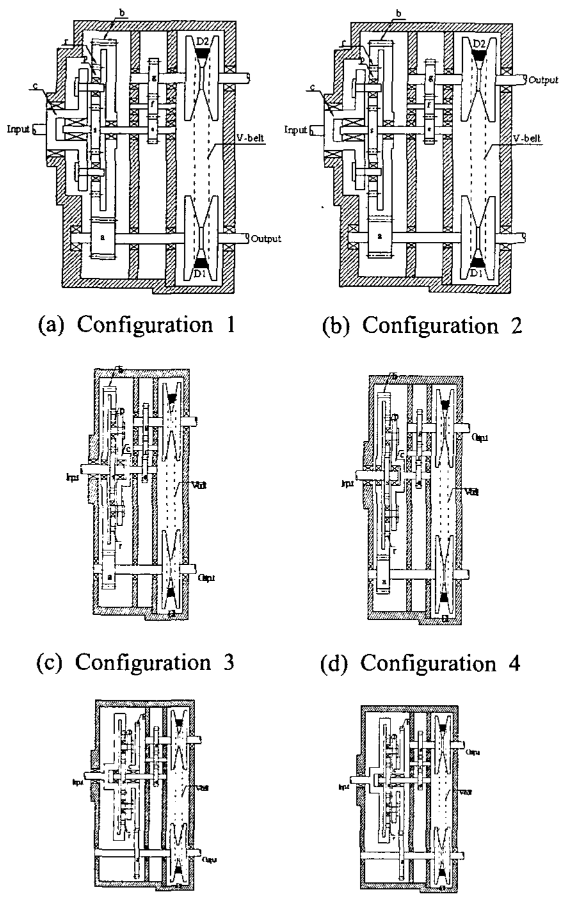
2.4 Power flows

In the CVT mechanism, power flow mode is divided into a power circulation mode and a power split mode[3]. A power circulation mode has a positive circulation mode and a negative power circulation mode. In the power split mode, there is no power circulation but input power is divided and flows in a forward(positive) direction through a CVU and a differential gear unit.

3. Proposed mechanisms and relations

3.1 Mechanism description

There are six possible ways of connecting the V-belt type CVU with two shafts and the 2K-H I type differential gear unit with three shafts in order to form the output coupled type CVT mechanisms, which are schematically illustrated in Fig.3. From these mechanisms it is known that the direction of rotation between a ring gear and a sun gear can be varied by means of an idler gear(f). In Fig. 3 each configuration has two configurations whether an idler gear(f) is applied or not, therefore, the proposed CVT mechanisms are twelve configurations. In the twelve mechanisms, six configurations have a power circulation mode and the others have a power split mode.



(a) Configuration 1 (b) Configuration 2

(c) Configuration 3 (d) Configuration 4

(e) Configuration 5 (f) Configuration 6

Fig. 3 Proposed mechanism configurations for an output coupled type CVT

3.2 Power circulation modes

All arguments regarding the judgements of power flows and the derivation of theoretical relations were discussed in the earlier publication of authors[12]. Configurations 1 and 2 with an idler gear(f), and configurations 3, 4, 5 and 6 without an idler gear(f) have a power circulation mode.

3.3 Power split modes

Configurations 1 and 2 without an idler gear(f), and configurations 3, 4, 5 and 6 with an idler gear(f) have a power split mode. The theoretical relations are shown in the earlier publication of authors[12].

4. Parametric analysis

4.1 Parameters and assumptions

A parametric approach is to perform parametric sensitivity analysis. In the parametric analysis, a parametric characterization is made based on the three independent parameters to evaluate the performance of the output coupled type CVT mechanisms, which are the basic gear ratio (zr/zs) of the differential gear unit, gear ratio zg/ze and zb/za. The parameters and associated value ranges are provided in Table 1.

Table 1 Ranges of parameters for parametric analysis

parameters	ranges	remarks
z_r/z_s	2.5~4.5	$z_b/z_a = z_h/z_a = 2.0$ $z_g/z_e = 1.0$
z_b/z_a, z_h/z_a	1/3~3.0	$z_r/z_s = 3.0$ $z_g/z_e = 1.0$
z_g/z_e	1/3~3.0	$z_r/z_s = 3.0$ $z_g/z_e = 1.0$

The mating efficiencies of gears (a, b, e, g, h, f and the differential gear unit) and the CVU efficiency are necessary in order to calculate the overall efficiency of CVT mechanisms as in Fig.3, which are shown in Table 2[10-12].

Table 2 Efficiencies of gears and the CVU

a differential gear unit & gear trains	
η_{rp}=0.992, η_{sp}=0.982, η_{ef}=0.982, η_{fg}=0.982 η_{eg}=0.982, η_{ab}=0.982, η_{ah}=0.982	
a continuously variable unit	
speed ratios	efficiency of the CVU
0.50	0.938
0.66	0.904
1.00	0.870
2.00	0.824

The speed ratio range of the V-belt type CVU is capable of 0.5～2.0. Many experimental studies are performed in the speed ratio 0.5, 0.66, 1.0 and 2.0 so as to determine the efficiency of the CVU, which may be used as the input data of parametric analysis. For the CVU the efficiencies between measured data are determined as linear interpolation[10-12].

For the theoretical analysis several assumptions must be defined, which are identical to previous publications[10-12]. The friction coefficient of gear tooth flank is assumed to 0.1, and all gears composed of the CVT mechanisms are standard spur gears. Backlash is ignored. In the differential gear unit the distributions of transmitted power between planet gears are assumed uniformly.

4.2 Power circulation mode

The efficiency and the speed ratio characteristics of the power circulation CVT mechanisms are calculated as changing the three independent parameters. Fig. 4 shows the speed ratio simulation results as the change of differential gear ratio (zr/zs) for configuration 1. The speed ratio of configuration 1 is the hyperbolic curve that diverges at the specific CVU speed ratio, where the rotating direction of output shaft is reverted. In the input coupled CVT geared neutral, the output power and the speed ratio is zero, is generated at this point[10,11].

In the power circulation mode, the speed ratios of all configurations are hyperbolic curves, therefore, it is impossible to be used as the CVT mechanism. In spite of no divergency as changing the other parameters, it is of no value because circulated power in the mechanism is larger than the power split mode and reduces the life cycle of CVT mechanisms.

Fig. 5 shows the theoretical efficiency simulation results as the change of differential gear ratio (zr/zs) for configuration 1. In the neighborhood of specific CVU speed ratio, where the rotating direction of output shaft is reverted, efficiency is near to zero. In the power circulation mode, the other configurations have a trend similar to the configuration 1. As changing the other parameters, each efficiencies are similar to Fig. 5. Since the efficiency characteristics are also inferior, it is preferable not to used as the CVT mechanisms.

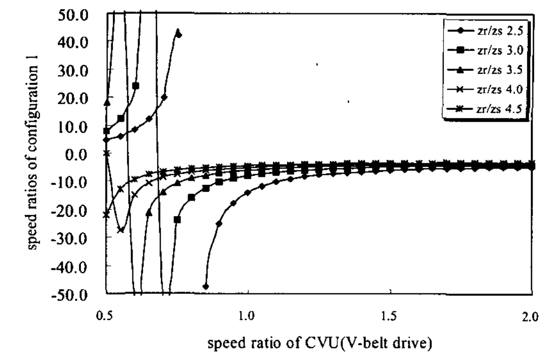


Fig. 4 Speed ratios of configuration 1 (power circulation) as changing the basic gear ratio (z_r/z_s)

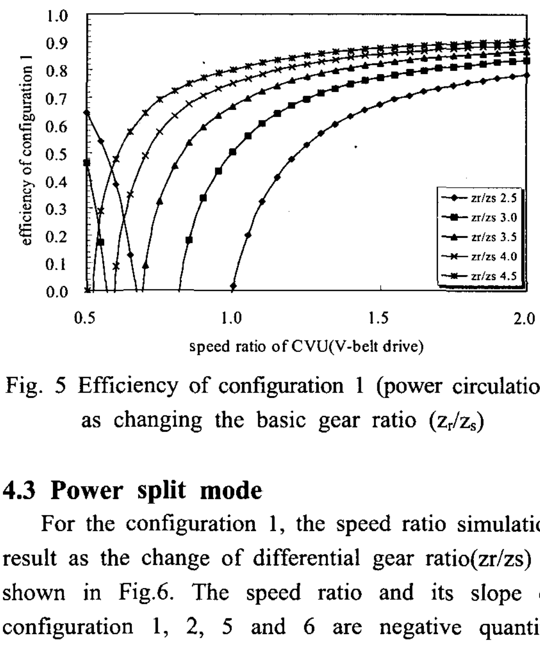


Fig. 5 Efficiency of configuration 1 (power circulation) as changing the basic gear ratio (z_r/z_s)

4.3 Power split mode

For the configuration 1, the speed ratio simulation result as the change of differential gear ratio(zr/zs) is shown in Fig.6. The speed ratio and its slope of configuration 1, 2, 5 and 6 are negative quantity (opposite to the input shaft), but configuration 3 and 4 have a positive quantity. The speed ratios of configuration 1, 2, 5 and 6 are proportional to the increase of differential gear ratio (zr/zs), but configuration 3 and 4 are inversely proportional. The speed ratios of all configurations are proportional to the increase of the gear ratio zb/za, but are inversely proportional to the increase of the gear ratio zg/ze. All configurations have an only one-directional motion.

For the configuration 1, the theoretical efficiency simulation result as the change of differential gear ratio (zr/zs) is shown in Fig. 7. For all configurations, the change of differential gear ratio (zr/zs) hardly affect efficiency. The efficiencies of configurations 2, 4 and 6 are proportional to the increase of the gear ratios zb/za and zg/ze, and configuration 1, 3, 5 are inversely proportional. In the power split mode, the speed ratio of the CVU has no large influence on the efficiency.

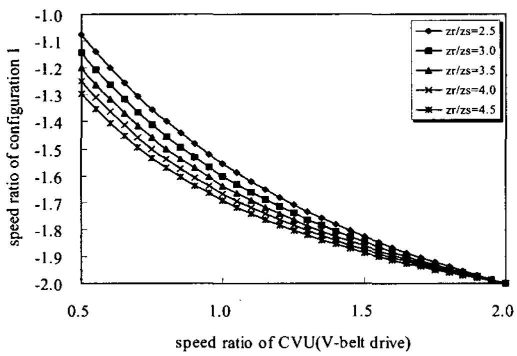


Fig. 6 Speed ratios of configuration 1 (power split mode) as changing the basic gear ratio (z_r/z_s)

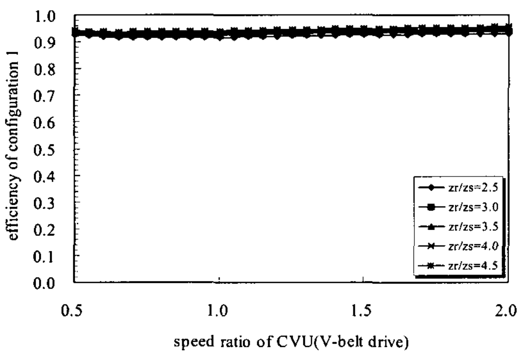


Fig.7 Efficiency of configuration 1 (power split mode) as changing the basic gear ratio (z_r/z_s)

As the change of differential gear ratio (zr/zs), the power ratio (Pcvu/Pi) simulation result of configuration 1 is shown in Fig. 8. The power ratio (Pcvu/Pi) of configuration 2, 4 and 6 are proportional to the increase of differential gear ratio (zr/zs), inversely proportional to the increase of gear ratio zb/za and zg/ze. That of configuration 1, 3 and 5 are inversely proportional to the increase of differential gear ratio (zr/zs), and proportional to the increase of gear ratio zb/za and zg/ze. It has an opposite trend to the efficiency because the efficiency of the CVU is lower than the that of the differential gear unit.

As the change of differential gear ratio (zr/zs), the power ratio (Pdif/Pi) simulation result of configuration 1 is shown in Fig. 9. For the all configurations, the power ratio (Pdif/Pi) has an opposite trend to the power ratio (Pcvu/Pi), but has a similar trend to the efficiency.

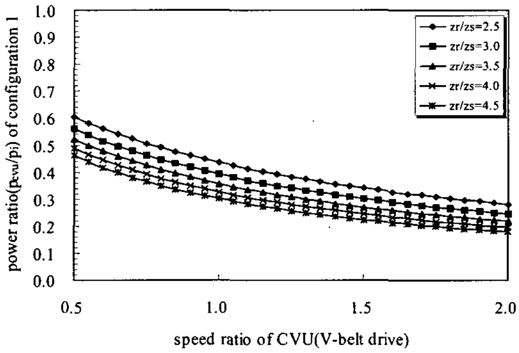


Fig. 8 Power ratio (P_{cvu}/P_i) of configuration 1 (power split) as changing the basic gear ratio (z_r/z_s)

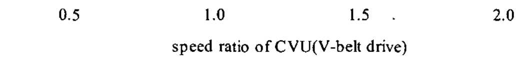


Fig. 9 Power ratio (P_{dif}/P_i) of configuration 1 (power split) as changing the basic gear ratio (z_r/z_s)

5. Experimental studies

5.1 Experimental bench

The experimental bench is a fixed center compound drive connected to a driving motor and a load device, and instrumented to measure the speeds and the torques of the input and the output shaft. A driving motor used is an induction motor (11kW) linked to the input shaft. A load device is an electro-magnetic particle brake connected to the output shaft[11].

Fig. 10 is the schematic drawing of the experimental bench installed in the laboratory. The differential gear unit and other gears manufactured are composed of standard spur gears, whose addendum modification coefficient is zero and addendum is equal to module (2.5㎜). The V-belt type CVU is basically a symmetrical compound drive with variable-diameter pulleys. The center distance of the CVU is 279㎜ and the maximum diameter of the V-belt pulley is 216㎜, which contains a toothed cog rubber V-belt. The torque meter is a line of shaft-to-shaft rotary torque sensor having measuring range 0~100Nm. The speed meter is an optical fiber speed sensor having measuring range 60~2400rpm. The load device (brake) linked to the output shaft may be controlled to 100Nm automatically, which generates braking force for the torques of the input shaft and the output shaft. When the load at the output shaft is increased the speed of a driving motor will be decreased irregularly. Therefore the speed of a driving motor must be controlled to preserve an ordered value regardless of the applied load at the output shaft. The warming up of the experimental bench is performed during 30 minutes before experiment.

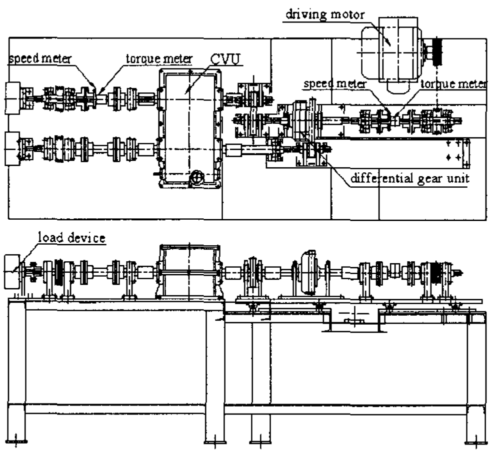


Fig. 10 Schematic drawing of the experimental bench

5.2 Power circulation mode

Six configurations for the power circulation mode were individually experimented. The experimental results for efficiency and speed ratio were compared with the theoretical analysis results. The differential gear unit with zs=24, zp=24, zr=72, zb=90 and zh=90 is used, and other gears(e, g, f and a) have different number of teeth, ze=50, zg=25, zf=18, za=45.

Fig. 11(a)-(c) are the plots of the overall

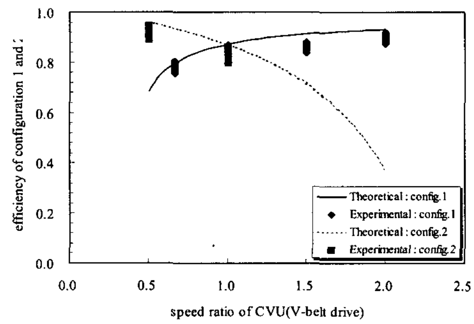


Fig. 11(a) Experimental and theoretical efficiency for configuration 1, 2(power circulation mode)

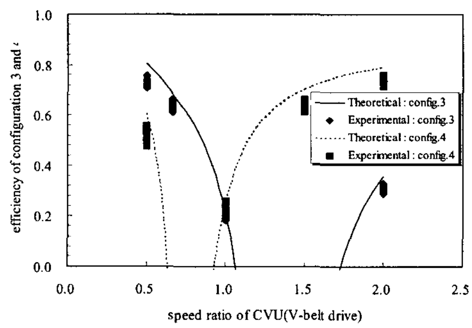


Fig. 11(b) Experimental and theoretical efficiency for configuration 3, 4(power circulation mode)

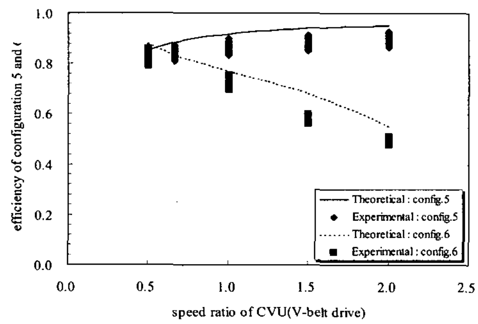


Fig. 11(c) Experimental and theoretical efficiency for configuration 5, 6(power circulation mode) efficiency versus the speed ratio of the CVU, which show comparisons between the experimental data and the theoretical results for each of the six power circulation modes. Although there is somewhat scatter in the experimental data for each of them, the experimental results have the trends similar to the theoretical results. The differences between the experimental results and the theoretical results are caused by the inertia and clearances of the experiment bench components (gears, shafts, bearings, etc.), disparity between the actual conditions and the conditions used in simulation.

For overall speed ratio the experimental data of the six power circulation modes were compared with the theoretical results. Fig. 12(a)-(c) are the plots of the overall speed ratio versus the speed ratio of the CVU. In spite of somewhat scatter in the experimental data, the experimental results have the trends similar to the theoretical results.

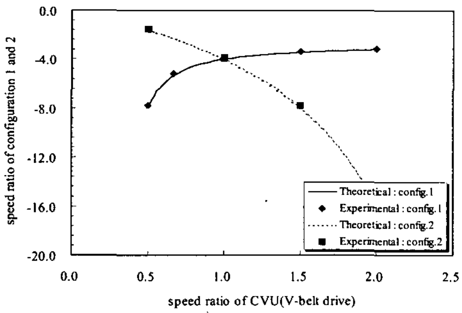


Fig. 12(a) Experimental and theoretical speed ratio for configuration 1, 2(power circulation mode)

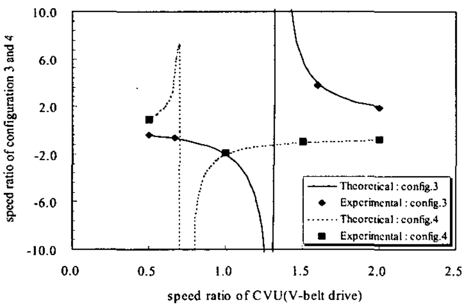


Fig. 12(b) Experimental and theoretical speed ratio for configuration 3, 4(power circulation mode)

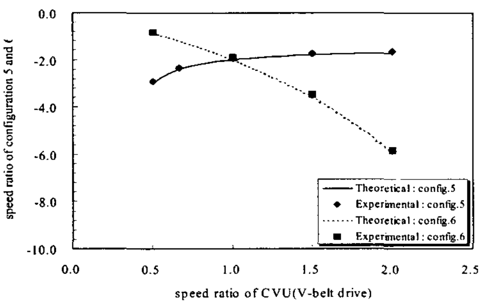


Fig. 12(c) Experimental and theoretical speed ratio for configuration 5, 6(power circulation mode)

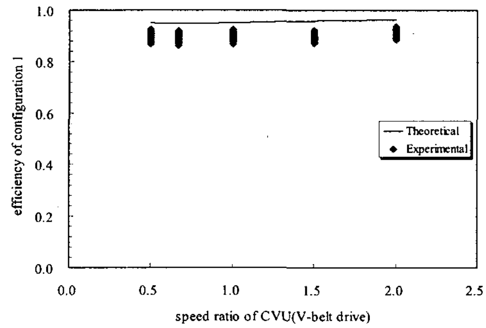


Fig.13(a) Experimental and theoretical efficiency for configuration 1 (power split mode)

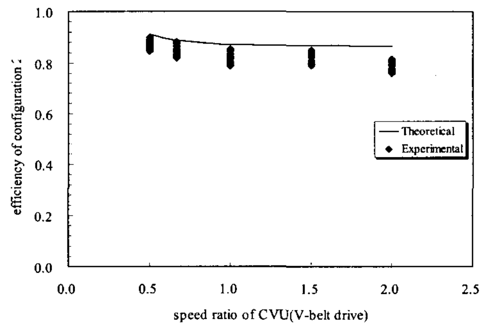


Fig.13(b) Experimental and theoretical efficiency for configuration 2 (power split mode)

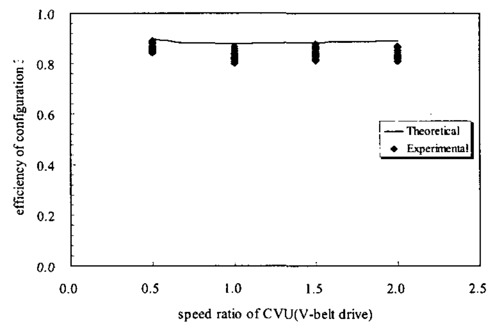


Fig.13(c) Experimental and theoretical efficiency for configuration 3 (power split mode)

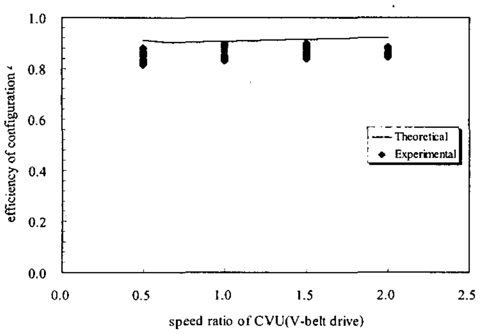


Fig.13(d) Experimental and theoretical efficiency for configuration 4 (power split mode)

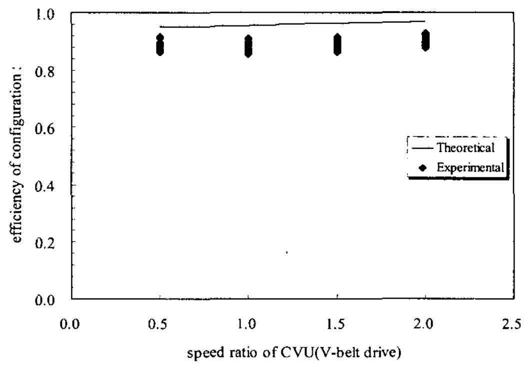


Fig.13(e) Experimental and theoretical efficiency for configuration 5 (power split mode)

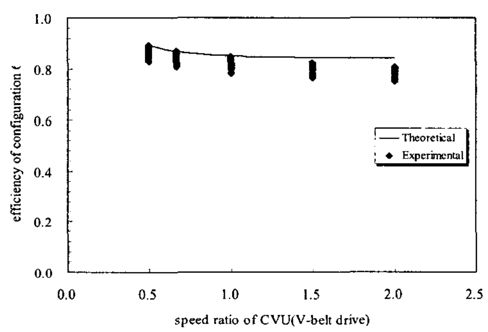


Fig.13(f) Experimental and theoretical efficiency for configuration 6 (power split mode)

5.3 Power split mode

Fig. 13(a)-(f) show comparisons between the experimental data and the theoretical efficiency for each of the six power split modes. The experimental results in the each speed ratio of the CVU have also the trends similar to the theoretical results.

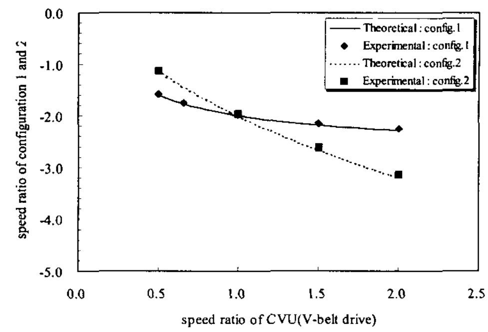


Fig. 14(a) Experimental and theoretical speed ratio for configuration 1, 2 (power split mode)

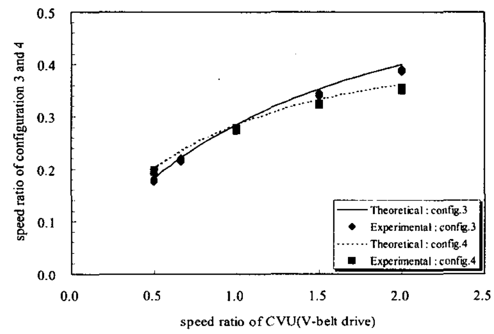


Fig. 14(b) Experimental and theoretical speed ratio for configuration 3, 4 (power split mode)

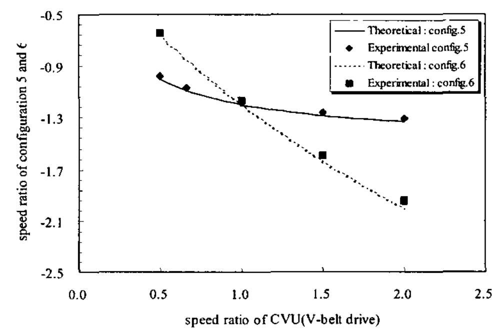


Fig. 14(c) Experimental and theoretical speed ratio for configuration 5, 6 (power split mode)

Fig. 14(a)-(c) show comparisons between the experimental data and the theoretical results for speed ratios. There is no neutral point and all configurations have an only one-directional motion. It is shown that the experimental results have the trends similar to the theoretical results. The CVT mechanism having a power split mode must be equipped with a special component which may generate a neutral point to be of practical use for automobiles.

6. Conclusions

For twelve output coupled type CVT mechanisms composed of a 2K-H I type differential gear unit and a V-belt type CVU with a variable-diameter pulley, parametric analysis and experimental studies have been performed.

1) In the power circulation mode, it is impossible to be used as the CVT mechanism because the speed ratios of all configurations are hyperbolic curves.
2) From the comparisons between the theoretical results and the experimental results, it has been shown that theoretical relations are valid.
3) The results presented in the parametric analysis provide a useful insight into the performance and design of twelve output coupled CVT mechanisms.

References

1. R.H.Macmillan, "Power Flow and Loss in Differential Mechanisms," Journal of Mechanical Engineering Science, Vol. 3, No. 1, pp. 37-41, 1961.
2. R. H. Macmillan, and P. B. Davies, "Analytical Study of Systems for Bifurcated Power Transmission," Journal of Mechanical Engineering Science, Vol. 7, No. 1, pp. 40-47, 1965.
3. G.White, "Properties of Differential Transmissions," The Engineer, Technical Contribution Section, pp. 105-111, 1967.
4. D. Yu, and N.Beachley, "On the Mechanical Efficiency of Differential Gearing," ASME Journal of Mechanisms, Transmissions, and Automation in Design, Vol. 107, pp. 61-67, 1985.
5. M. Morozumi, S. Kishi, Y. Furukawa, and H. Misawa, "A Study of Variable Speed Transmission with Differential Gear," Journal of Japan Automotive technology Association, No. 46, pp. 45-49, 1990.
6. S. Kishi, M. Morozumi, Y. Furukawa, H. Misawa, and H. Miyata, "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, 1992.
7. Victor H. Mucino and James E. Smith, "Parametric Modeling and Analysis of a Planetary Gear-CVT Mechanism," SAE Paper 940519, pp. 113-123, 1994.
8. M. Morozumi, and S.Kishi, "A Mechanical Consideration on CVT with a Differential Gearing(1)," Mechanical Research (Japanese), Vol. 49, No. 5, pp. 50-58, 1997.
9. M. Morozumi, and S. Kishi, "A Mechanical Consideration on CVT with a Differential Gearing(2)," Mechanical Research (Japanese), Vol. 49, No. 10, pp. 42-51, 1997.
10. Yeon-Su Kim, and Sang-Hoon Choi, "Power Flow and Efficiency of Input Coupled type CVT combined Differential Gear Unit," Journal of KSPE, Vol. 17, No. 11, pp. 141-150, 2000.
11. Yeon-Su Kim, and Sang-Hoon Choi, "Experimental Study on the Input Coupled type CVT combined of a Differential Gear Unit and a V-belt type CVU," International Journal of KSPE, Vol. 2. No. 1, pp. 43-55, 2001.
12. Sang-Hoon Choi, and Yeon-Su Kim, "Characteristics on the Output Coupled type CVT combined 2K-H Differential Gear Unit and V-belt Drive," Journal of KSPE, Vol. 18, No. 3, pp. 205-215, 2001.
13. Yeon-Su Kim, Sung-Uk Choi, and Sang-Hoon Choi, "A Study on the Efficiency Analysis of 2K-H Type Planetary Gear Train," Journal of KSPE, Vol. 17, No. 3, pp. 200-207, 2000.
14. Yeon-Su Kim, and Sang-Hoon Choi, "Interference and Efficiency Analysis of 2K-H I type Differential Gear Unit," International Journal of KSPE, Vol. 1. No. 1, pp. 5-14, 2000.