Experimental Study on the Input Coupled type CVT combined a Differential Gear and a V-Belt type CVU

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ABSTRACT

A continuously variable transmission(CVT) mechanism composed of one differential gear unit and one continuously variable unit(CVU) can be classified according to the coupling of CVU and the direction of power flows. This mechanism has many advantages which are the decrease of CVT size, the increase of overall efficiency, the extension of speed ratio range and the generation of geared neutral. The CVT mechanism considered here is the input coupled type which combines the functions of a 2K-H I type differential gear unit and a V-belt type CVU. One shaft of the CVU is connected directly to the input 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. Some useful comparisons between theoretical analysis and experimental results are presented. General properties also are discussed, which connect following power flow modes : (a) power circulation mode; (b) power split mode.

Keywords : Continuously variable transmission, Input coupled, 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

i = overall speed ratio of a CVT

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 one differential gear unit and one continuously variable unit 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. Especially the composition of a 2K-H I type differential gear unit and a V-belt type CVU with a variable-diameter pulley makes it possible for various configurations.

Many previous contributions related to this mechanism composed of a differential gear unit and a CVU have been performed. A computational scheme for estimating the overall efficiency and an investigation on the overall efficiency in this mechanism have been executed[1,2]. However these are not in agreement with the experimental results because of the assumptions that the efficiency of a CVU unit is not affected by the transmission ratio and that a differential gear unit is perfectly efficient. According to the coupling of a CVU and the direction of internal power flow, this mechanism have been classified and 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]. However this contribution was on the general characteristics and not verified by experiment. Analytical methods for the efficiency analysis of the mechanism have been suggested[4]. Two types of the CVT composed of a hypocycloid type differential gearing and a V-belt drive have been developed, theoretical analysis and experimental studies have been executed[5,6]. Three basic configurations similar to the mechanism herein described, which do not require clutches, have been proposed. Futhermore parametric analysis and optimum design have been executed[7]. For the input coupled type and the output coupled type CVT composed of a 2K-H I type differential gear unit and a V-belt type CVU, theoretical efficiency, power flow and speed ratio have been derived[8,9]. More recently, authors have developed twelve basic 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 derived, some of them were proven by experimental studies[10].

Based on authors' previous work[10], theoretical relations associated with efficiency and speed ratio for the twelve input coupled type CVT mechanisms, six of them have a power circulation mode and the others have a power split mode, are investigated through experimental studies. From the comparisons between theoretical and experimental results, it is shown that theoretical relations are valid. General properties also are discussed as the power flow mode.

2. General definitions

2.1 V-belt type CVU with a variable pulley

A V-belt drive with pulleys whose diameters may be varied is a continuously variable unit that can transmit power in either direction of rotation, which is shown in Fig.1. In recent years it has been the most common type of practical use for automobiles, where it may be applied to a small vehicle. The pulley diameters may be varied in various ways, depending on the desired speed ratio and the needed type of control unit. A V-belt type CVU considered here 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.

In recent developments the control of speed ratio is set by a precise hydraulic device as a function of demanded torque and speed, which is based on a steel V-belt and a variable pulley

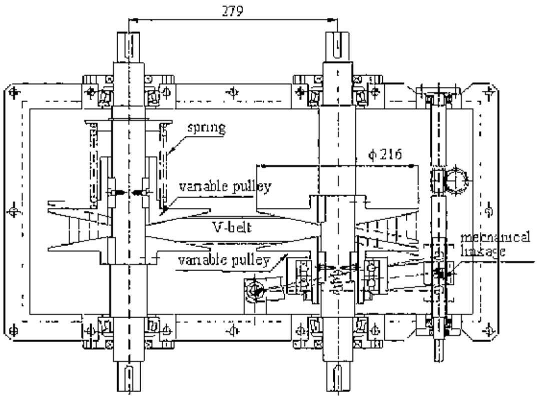


Fig.1 V-belt type CVU with two Variable pulleys

2.2 2K-H I type differential gear unit

A 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, a planet gear and a carrier. The shafts of a ring gear, a sun gear and a carrier are called basic shafts which are concentric. A 2K-H I type differential gear unit considered here has no basic shaft fixed and may provide a differential action.

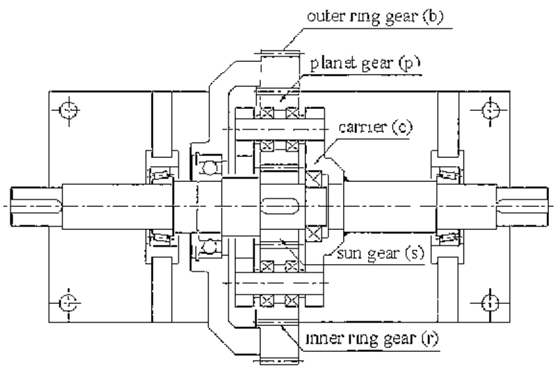


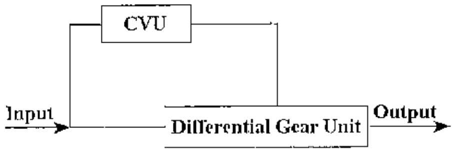
Fig.2 2K-H I type differential gear unit

In case that a carrier is fixed the efficiency of a differential gear unit is defined as the basic efficiency, which 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}). Therefore the basic efficiency of a differential gear unit can be calculated as

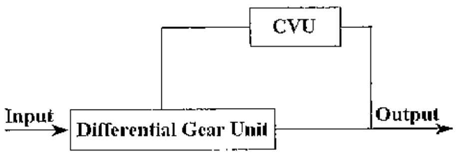
$$\eta_0 = \eta_{rp}\eta_{sp} \tag{1}$$

2.3 Input coupled type CVT

The two block diagrams of Fig.3 are distinguished by the connections of CVU shafts. In both instances the CVU is coupled directly to the differential gear unit and with Fig.3(a) the remaining shaft of the CVU is linked to the input shaft, whereas with Fig.3(b) it is linked to the output shaft.



(a) Input-coupled type



(b) Output-coupled type

Fig.3 Two basic types of a CVT mechanism

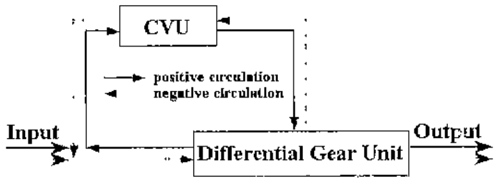
Each block diagram is an inversion of the other, but the block diagram relations are defined only by a distinct characteristics. In this paper the input coupled type CVT is only considered(Fig.3(a)).

2.4 Classification of power flow in a CVT

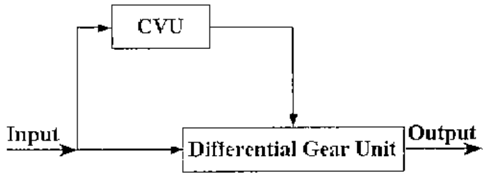
A physical interpretation of power flow is useful in the design of a CVT mechanism and these power flows, a power circulation mode and a power split mode, are classified as shown in Fig.4.

Fig.4(a) shows how power can be back from a differential gear unit and there are two power circulation modes. One defined as a positive circulation mode is noticed that power flow through the CVU is in the forward direction to the output shaft, the other defined as a negative power circulation mode is in the opposite direction to positive circulation mode.

In Fig.4(b) 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.



(a) Power circulation mode



(b) Power split mode

Fig.4 Power flow modes in a CVT mechanism

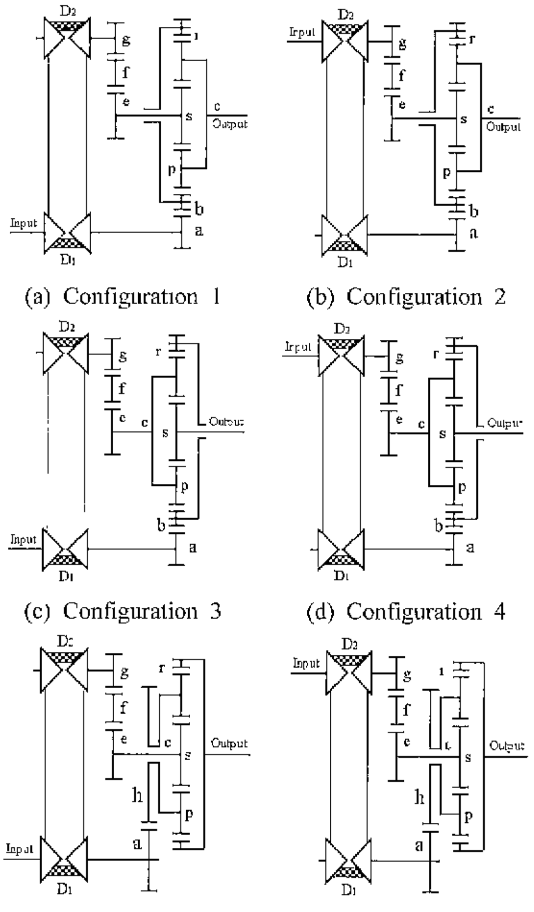
3. Proposed mechanisms and relations

Authors have proposed twelve basic configurations for the input coupled type CVT and fundamental relations, where the CVT have been composed of a 2K-H I type differential gear unit and a V-belt type CVU with a variable-diameter pulley[10]. The first subsection is concerned with a review of twelve configurations. The last two subsections will describe theoretical relations(efficiency and speed ratio) for a power circulation mode and a power split mode.

3.1 Mechanism description

There are six possible ways of connecting a V-belt type CVU with two shafts and a 2K-H I type differential gear unit with three shafts in order to form the CVT mechanisms considered here, which are schematically illustrated in Fig.5. 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.5 each configuration has two configurations whether an idler gear(f) is applied or not, therefore, the proposed CVT mechanisms are twelve configurations.

Mechanisms as shown in Fig.5 use only a 2K-H I type differential gear unit and a V-belt type CVU directly connected to provide a continuously variable transmission. The combined features of two main components(a differential gear unit and a CVU) do not require the use of clutches. In the twelve mechanisms, six configurations of them 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.5 Proposed mechanism configurations for an input coupled type CVT

3.2 Power circulation modes

All arguments regarding the judgements of power flows(a power circulation mode and a power split mode) and the derivation of theoretical relations(speed ratio and efficiency) were discussed in the earlier publication of authors[10]. In this paper, therefore, theoretical procedures stated above is omitted.

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. For these configurations the theoretical relations associated with speed ratio and efficiency are shown in Table 1. The resulting efficiencies between a CVU and gear trains except a differential gear unit are as follows :

- configuration 1 and 2 with an idler gear(f)

$$\eta_0' = \eta_{ab}\eta_{ef}\eta_{fg}\eta_{CVU} \qquad (2)$$

- configuration 3 and 4 without an idler gear(f)

$$\eta_0' = \eta_{ab}\eta_{eg}\eta_{CVU} \qquad (3)$$

- configuration 5 and 6 without an idler gear(f)

$$\eta_0' = \eta_{ah}\eta_{eg}\eta_{CVU} \qquad (4)$$

where :

η_{ab} = mating efficiency between a gear(a) and an outer ring gear(b)

η_{ah} = mating efficiency between a gear(a) and (h)

η_{ef} = mating efficiency between a gear(e) and an idler gear(f)

η_{fg} = mating efficiency between an idler gear(f) and a gear(g)

η_{eg} = mating efficiency between a gear(e) and (g)

η_{CVU} = efficiency of a CVU

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. For these configurations the theoretical relations associated with speed ratio and efficiency are shown in Table 2. The resulting efficiencies between a CVU and gear trains except a differential gear unit are as follows :

- configuration 1 and 2 without an idler gear(f)

$$\eta_0' = \eta_{ah}\eta_{eg}\eta_{CVU} \qquad (5)$$

- configuration 3 and 4 with an idler gear(f)

$$\eta_0' = \eta_{ab}\eta_{ef}\eta_{fg}\eta_{CVU} \qquad (6)$$

- configuration 5 and 6 with an idler gear(f)

$$\eta_0' = \eta_{ah}\eta_{ef}\eta_{fg}\eta_{CVU} \qquad (7)$$

Table 1 Speed ratios and efficiencies for six power circulation modes

config-ration	idler gear (f)	criteria of power flow	i_{eq}	speed ratios(i)	overall efficiencies(η)	power flow mode
1	Included	$i_{eq} > i_0$	$\frac{D_1 z_g z_b}{D_2 z_e z_a}$	$\frac{i_{eq}-i_0}{1+i_0}\frac{z_a}{z_b}$	$\frac{\eta_0'(1+\eta_0 i_0)(i_{eq}-i_0)}{(1+i_0)(i_{eq}-\eta_0\eta_0' i_0)}$	positive circulation
		$i_{eq} < i_0$		$-\frac{i_0-i_{eq}}{1+i_0}\frac{z_a}{z_b}$	$\frac{(\eta_0+i_0)(i_0-i_{eq})}{(1+i_0)(i_0-\eta_0\eta_0' i_{eq})}$	negative circulation
2	Included	$i_{eq} > i_0$	$\frac{D_1 z_g z_b}{D_2 z_e z_a}$	$\frac{i_{eq}-i_0}{i_{eq}(1+i_0)}\frac{z_g}{z_e}$	$\frac{(1+\eta_0 i_0)(i_{eq}-i_0)}{(1+i_0)(i_{eq}-\eta_0\eta_0' i_0)}$	negative circulation
		$i_{eq} < i_0$		$-\frac{i_0-i_{eq}}{i_{eq}(1+i_0)}\frac{z_g}{z_e}$	$\frac{\eta_0'(\eta_0+i_0)(i_0-i_{eq})}{(1+i_0)(i_0-\eta_0\eta_0' i_{eq})}$	positive circulation
3	None	$1+i_0 > i_0 i_{eq}$	$\frac{D_2 z_e z_a}{D_1 z_g z_b}$	$-\frac{1+i_0-i_0 i_{eq}}{i_{eq}}\frac{z_a}{z_b}$	$\frac{\eta_0\eta_0'(1+i_0-i_0 i_{eq})}{(\eta_0+i_0)-\eta_0^2\eta_0' i_0 i_{eq}}$	positive circulation
		$1+i_0 < i_0 i_{eq}$		$\frac{i_0 i_{eq}-(1+i_0)}{i_{eq}}\frac{z_a}{z_b}$	$\frac{\eta_0(1+i_0-i_0 i_{eq})}{\eta_0\eta_0'(1+\eta_0 i_0)-i_0 i_{eq}}$	negative circulation
4	None	$1+i_0 > i_0 i_{eq}$	$\frac{D_2 z_e z_a}{D_1 z_g z_b}$	$-(1+i_0-i_0 i_{eq})\frac{z_g}{z_e}$	$\frac{\eta_0(1+i_0-i_0 i_{eq})}{(\eta_0+i_0)-\eta_0^2\eta_0' i_0 i_{eq}}$	negative circulation
		$1+i_0 < i_0 i_{eq}$		$\{i_0 i_{eq}-(1+i_0)\}\frac{z_g}{z_e}$	$\frac{\eta_0\eta_0'(1+i_0-i_0 i_{eq})}{\eta_0\eta_0'(1+\eta_0 i_0)-i_0 i_{eq}}$	positive circulation
5	None	$1+i_0 > i_{eq}$	$\frac{D_1 z_g z_h}{D_2 z_e z_a}$	$-\frac{(1+i_0-i_{eq})}{i_0}\frac{z_a}{z_h}$	$\frac{\eta_0(1+i_0-i_{eq})}{1+\eta_0 i_0-\eta_0^2\eta_0' i_{eq}}$	negative circulation
		$1+i_0 < i_{eq}$		$\frac{i_{eq}-(1+i_0)}{i_0}\frac{z_a}{z_h}$	$\frac{\eta_0\eta_0'(1+i_0-i_{eq})}{\eta_0\eta_0'(\eta_0+i_0)-i_{eq}}$	positive circulation
6	None	$1+i_0 > i_{eq}$	$\frac{D_1 z_g z_h}{D_2 z_e z_a}$	$-\frac{(1+i_0-i_{eq})}{i_0 i_{eq}}\frac{z_g}{z_e}$	$\frac{\eta_0\eta_0'(1+i_0-i_{eq})}{1+\eta_0 i_0-\eta_0^2\eta_0' i_{eq}}$	positive circulation
		$1+i_0 < i_{eq}$		$\frac{i_{eq}-(1+i_0)}{i_0 i_{eq}}\frac{z_g}{z_e}$	$\eta=\frac{\eta_0(1+i_0-i_{eq})}{\eta_0\eta_0'(\eta_0+i_0)-i_{eq}}$	negative circulation

Table 2 Speed ratios and efficiencies for six power split modes

config-ration	idler gear (f)	i_{eq}	speed ratios(i)	overall efficiencies(η)	power flow mode
1	None	$\frac{D_1 z_g z_b}{D_2 z_e z_a}$	$-\frac{i_0+i_{eq}}{1+i_0}\frac{z_a}{z_b}$	$\frac{\eta_0'(\eta_0+i_0)(1+\eta_0 i_0)(i_0+i_{eq})}{(1+i_0)\{(1+\eta_0 i_0)i_0\eta_0'+(\eta_0+i_0)i_{eq}\}}$	power split
2	None	$\frac{D_1 z_g z_b}{D_2 z_e z_a}$	$-\frac{i_{eq}+i_0}{i_{eq}(1+i_0)}\frac{z_g}{z_e}$	$\frac{\eta_0'(\eta_0+i_0)(1+\eta_0 i_0)(i_{eq}+i_0)}{(1+i_0)\{i_0(1+\eta_0 i_0)+i_{eq}\eta_0'(\eta_0+i_0)\}}$	power split
3	Included	$\frac{D_2 z_e z_a}{D_1 z_g z_b}$	$\frac{1+i_0+i_0 i_{eq}}{i_{eq}}\frac{z_a}{z_b}$	$\frac{\eta_0\eta_0'(1+i_0+i_0 i_{eq})}{\eta_0+i_0(1+\eta_0' i_{eq})}$	power split
4	Included	$\frac{D_2 z_e z_a}{D_1 z_g z_b}$	$(1+i_0+i_0 i_{eq})\frac{z_g}{z_e}$	$\frac{\eta_0\eta_0'(1+i_0+i_0 i_{eq})}{\eta_0'(\eta_0+i_0)+i_0 i_{eq}}$	power split
5	Included	$\frac{D_1 z_g z_h}{D_2 z_e z_a}$	$-\frac{1+i_0-i_{eq}}{i_0}\frac{z_a}{z_h}$	$\frac{\eta_0\eta_0'(1+i_0+i_{eq})}{i_{eq}+\eta_0'(1+\eta_0 i_0)}$	power split
6	Included	$\frac{D_1 z_g z_h}{D_2 z_e z_a}$	$-\frac{1+i_0+i_{eq}}{i_0 i_{eq}}\frac{z_g}{z_e}$	$\frac{\eta_0\eta_0'(1+i_0+i_{eq})}{1+\eta_0 i_0+\eta_0' i_{eq}}$	power split

4. Simulation and experiment

4.1 Theoretical analysis

As in Fig.5 the CVT mechanisms are composed of three main components which are a differential gear unit, a CVU and other gears(gear(e), (g), (h) and an idler gear (f)). The specifications of three main components are shown in Table 3.

Table 3 Specifications of CVT manufactured

a differential gear unit & gear trains	
number of teeth	mating efficiencies
Z_s=24, Z_B=24, Z_r=72 Z_f=18, Z_a=30, Z_h=90 Z_b=90, Z_e=27, Z_g=27	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 a CVU
0.50	0.938
0.66	0.904
1.00	0.870
2.00	0.824

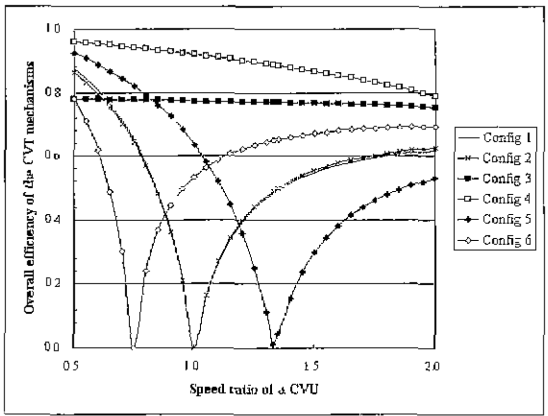
For the theoretical analysis several assumptions must be defined. In case of a differential gear unit and gear trains, the friction coefficient of tooth flank is assumed to 0.1 for the simplicity of calculation. All gears composed of the CVT mechanism are designed for a standard spur gear. Since backlash hardly affects efficiency, it is ignored. In a differential gear unit the distributions of transmitted power between planet gears are assumed uniformly. Based on these assumptions the mating efficiency of gear trains was calculated in previous publications[11,12].

The speed ratio of a V-belt type CVU is taken as a major parameter for the efficiency of it, so it must be capable of being adjusted arbitrarily. The V-belt type CVU considered here, therefore, is to have both variable 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. The speed ratio range 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 a CVU, which may be used as the input data of simulation program. For a CVU the efficiencies between measured data are determined as linear interpolation[10].

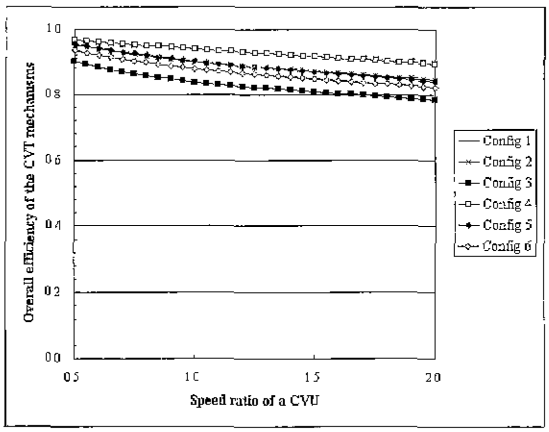
Based on Table 1, 2 and 3, the efficiency and the speed ratio characteristics of the CVT mechanisms as shown in Fig.5 are calculated as changing the speed ratio of a CVU. The simulation results are shown in Fig.6 and 7.

Fig.6 shows the efficiency simulation results as a power flow mode.

In case of a power circulation mode geared neutral, the output power and the speed ratio of the CVT is zero, is generated. However configurations 1, 2, 5 and 6 generate geared neutral, configurations 3 and 4 are capable of geared neutral as changing the gear ratios of a differential gear unit and gear trains.



(a) Power circulation mode



(b) power split mode

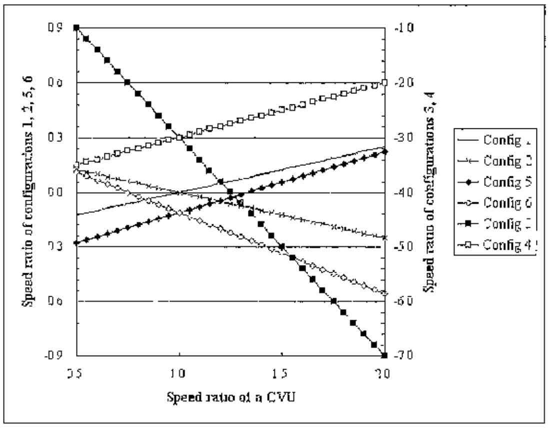
Fig.6 Theoretical efficiencies of the CVT proposed

In the event of a power split mode each efficiency is higher than the case of a power circulation mode because circulating power in the CVT mechanism can not be found. If the gear ratios of a differential gear unit and gear trains are adjusted the efficiency and the speed ratio of the CVT may be changed.

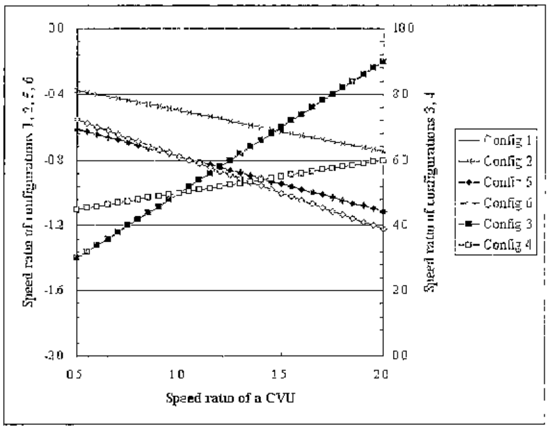
Fig.7 shows the speed ratio simulation results as a power flow mode.

In case of a power circulation mode configurations 1, 2, 5 and 6 have a neutral point and a forward/backward motion as the speed ratio of a CVU. Configurations 3 and 4 have a backward motion. If the gear ratios of a differential gear unit and gear trains, however, configurations 3 and 4 may have a bi-directional motion.

In the event of a power split mode all configurations have an only one-directional motion.



(a) Power circulation mode



(b) power split mode

Fig.7 Theoretical speed ratios of the CVT proposed

4.2 Experiment

The test rig 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. The speeds and the torques of the input and the output shaft are measured by two torque meters and two speed meters installed at each shaft. Therefore the overall efficiency(η) and the overall speed ratio(i) of the CVT can be calculated by relations (8) and (9) :

$$\eta = \frac{T_{out}\omega_{out}}{T_{in}\omega_{in}} \quad (8)$$

$$i = \frac{\omega_{out}}{\omega_{in}} \quad (9)$$

where T_{in} and T_{out} are the measured torques of the input and the output shaft, ω_{in} and ω_{out} are the measured speeds of the input and the output shaft.

Fig.8 is the schematic drawing of the test rig, and Fig.9 shows the photograph of it installed in the laboratory. The differential gear unit manufactured is a standard gear, whose addendum modification coefficient is zero and addendum is equal to module(2.5㎜). It is designed for spur gears with z_s=24, z_p=24, z_r=72 and z_b=90 whose cutter pressure angles are 20° . Other gears(gear(e), (g), (a) and an idler gear(f)) have the same specifications except the number of teeth. 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 a 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.

The test rig fixture is a rigid framework contained all components stated above, which is able to realize all configurations in Fig.5 and to change the speed ratio of it. 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 test rig is performed during 30 minutes before experiment.

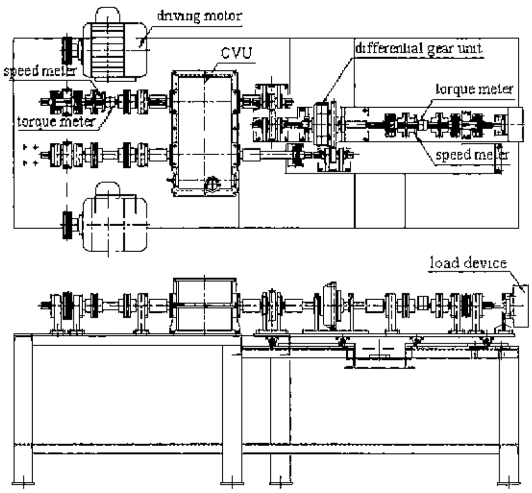


Fig. 8 Schematic drawing of the test rig

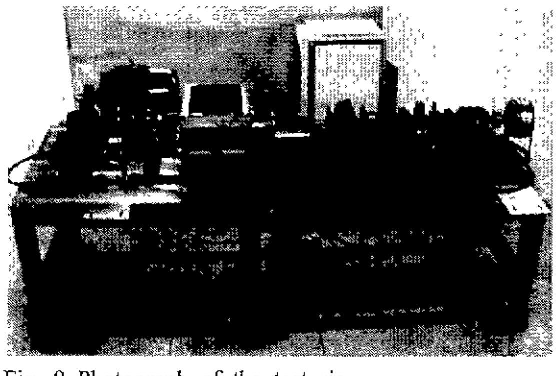


Fig. 9 Photograph of the test rig

5. Results and discussions

5.1 Overall efficiency

Each configuration of the CVT mechanism as shown in Fig.5 was individually experimented on a power circulation mode and a power split mode. The efficiency data for each of the twelve configurations (six power circulation modes and six power split modes) were compared with the theoretical analysis results of them.

Fig.10(a)-(f) are the plots of the overall efficiency versus the speed ratio of a CVU, which show comparisons between the experimental data and the theoretical results for each of the six power circulation modes. Configurations 1, 2, 5 and 6 generate geared neutral that the output power of them is zero and the efficiency of them is zero. Although there is somewhat scatter in the experimental data for each of them, the experimental results in the each speed ratio of a CVU 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 test rig components(gears, shafts, bearings, etc.), disparity between the actual conditions and the conditions used in simulation.

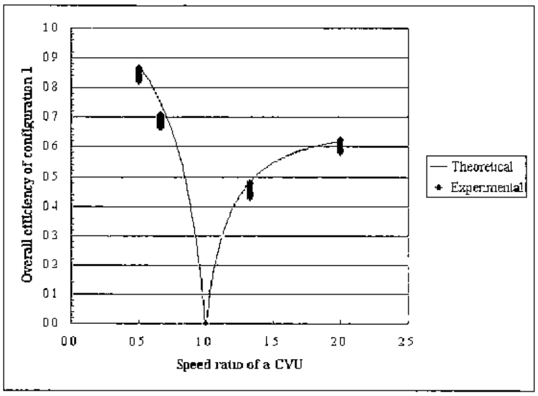


Fig.10(a) Experimental and theoretical efficiency for a power circulation mode(configuration 1)

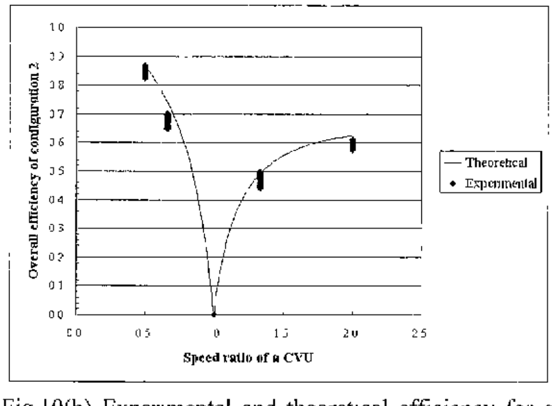


Fig.10(b) Experimental and theoretical efficiency for a power circulation mode(configuration 2)

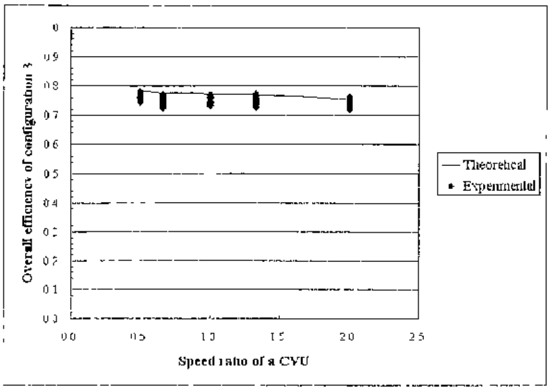


Fig.10(c) Experimental and theoretical efficiency for a power circulation mode(configuration 3)

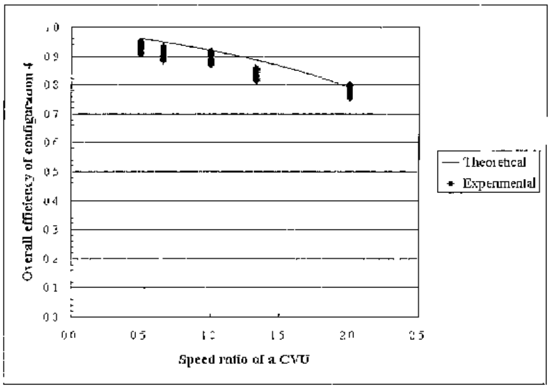


Fig.10(d) Experimental and theoretical efficiency for a power circulation mode(configuration 4)

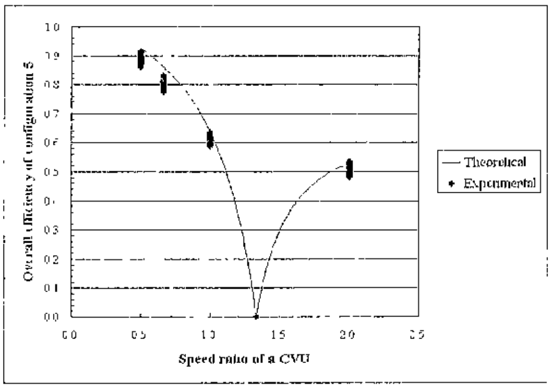


Fig.10(e) Experimental and theoretical efficiency for a power circulation mode(configuration 5)

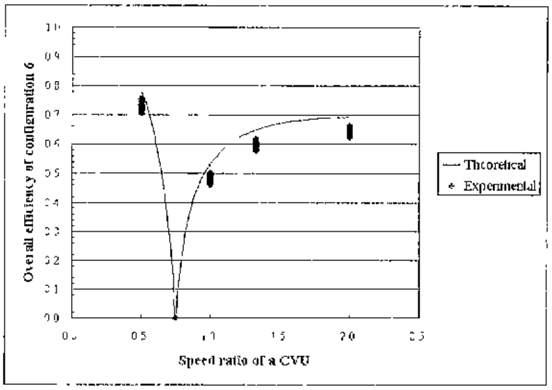


Fig.10(f) Experimental and theoretical efficiency for a power circulation mode(configuration 6)

Fig.11(a)-(f) are the plots of the overall efficiency versus the speed ratio of a CVU, which show comparisons between the experimental data and the theoretical results for each of the six power split modes. Although there is somewhat scatter in the experimental data for each of them, the experimental results in the each speed ratio of a CVU have the trends similar to the theoretical results. There is no geared neutral, but the overall efficiency of a power split mode is higher than that of a power circulation mode because circulating power in the CVT mechanism can not be found. Therefore input power is divided and flows through a CVU and a differential gear unit. If the gear ratios of the CVT mechanism are changed, the overall efficiency will be varied.

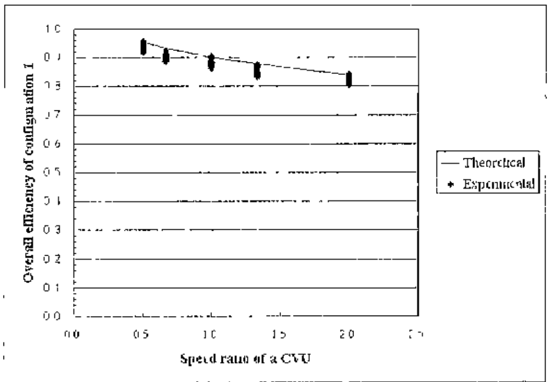


Fig.11(a) Experimental and theoretical efficiency for a power split mode(configuration 1)

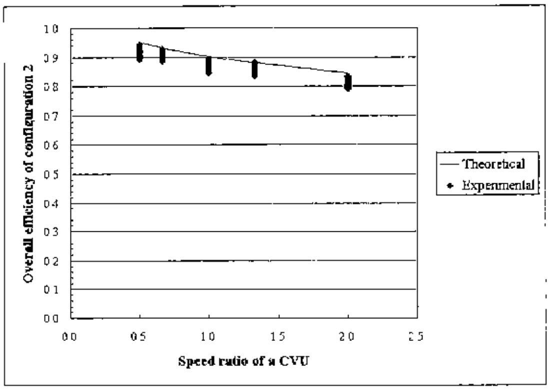


Fig.11(b) Experimental and theoretical efficiency for a power split mode(configuration 2)

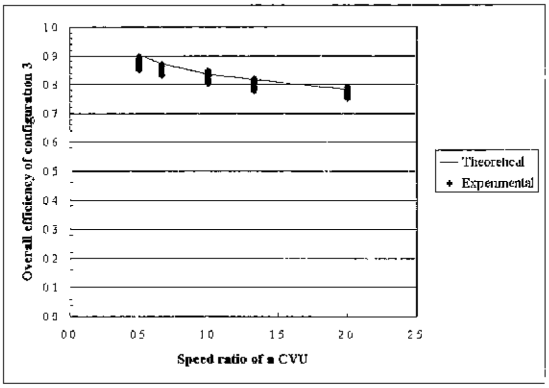


Fig.11(c) Experimental and theoretical efficiency for a power split mode(configuration 3)

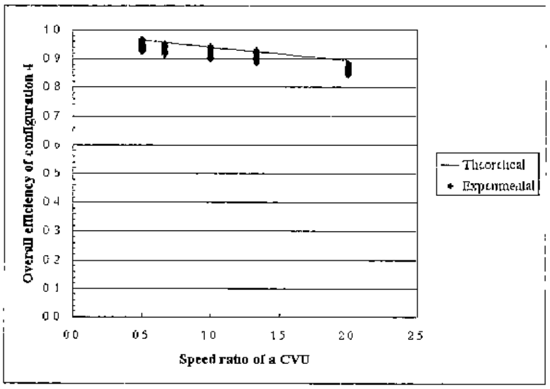


Fig.11(d) Experimental and theoretical efficiency for a power split mode(configuration 4)

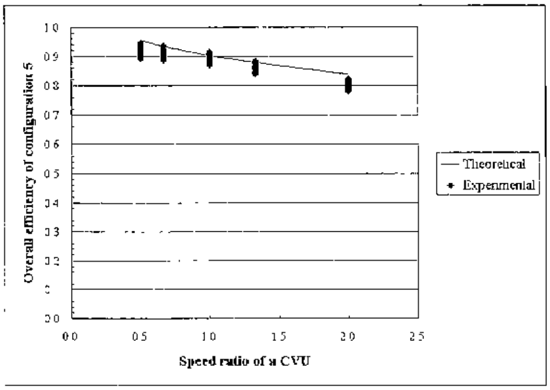


Fig.11(e) Experimental and theoretical efficiency for a power split mode(configuration 5)

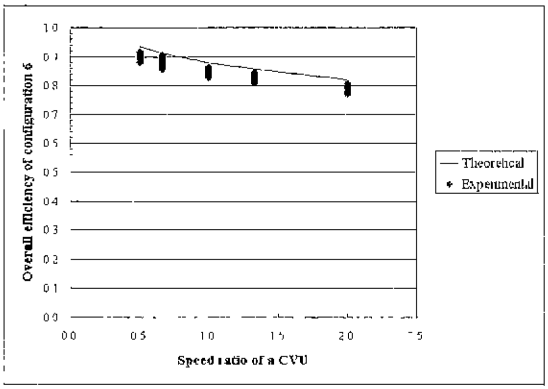


Fig.11(f) Experimental and theoretical efficiency for a power split mode(configuration 6)

5.2 Overall speed ratio

For overall speed ratio the experimental data for each of the twelve configurations(six power circulation modes and six power split modes) were compared with the theoretical analysis results of them.

Fig.12(a)-(f) are the plots of the overall speed ratio of the CVT versus the speed ratio of a CVU. Configurations 1, 2, 5 and 6 generate a neutral point and a forward/backward motion as the change of CVU speed ratio, where the overall speed ratio of the CVT is zero. It is shown that the neutral point is consistent with geared neutral in Fig.10. In spite of somewhat scatter in the experimental data the experimental results in the each speed ratio of a CVU have the trends similar to the theoretical results.

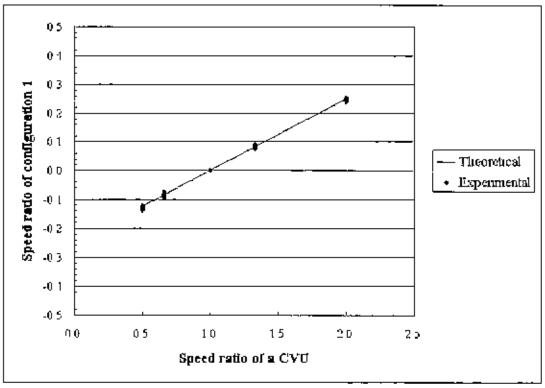


Fig.12(a) Experimental and theoretical speed ratio for a power circulation mode(configuration 1)

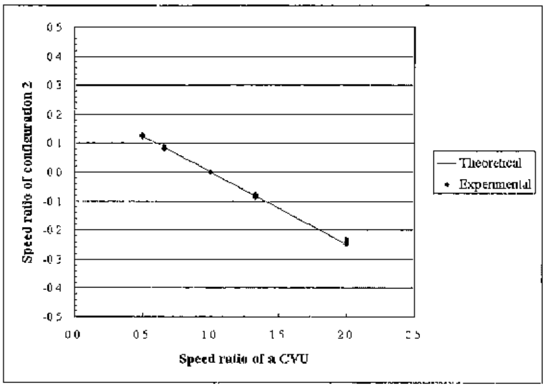


Fig.12(b) Experimental and theoretical speed ratio for a power circulation mode(configuration 2)

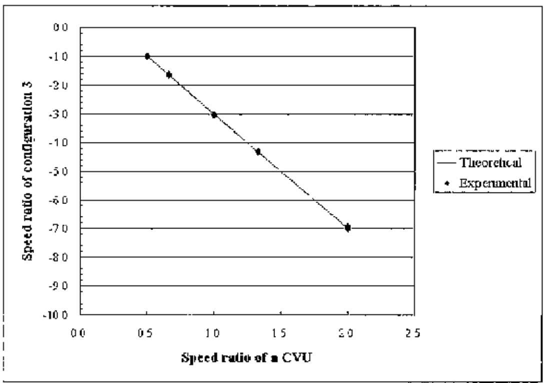


Fig.12(c) Experimental and theoretical speed ratio for a power circulation mode(configuration 3)

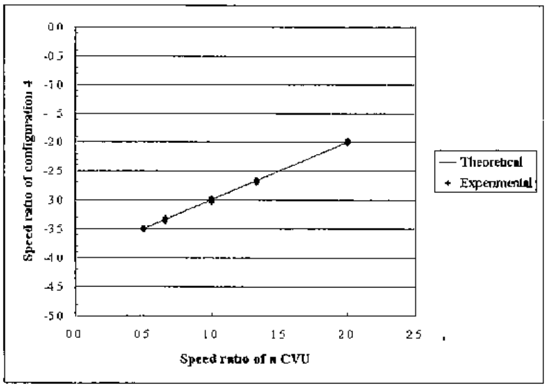


Fig.12(d) Experimental and theoretical speed ratio for a power circulation mode(configuration 4)

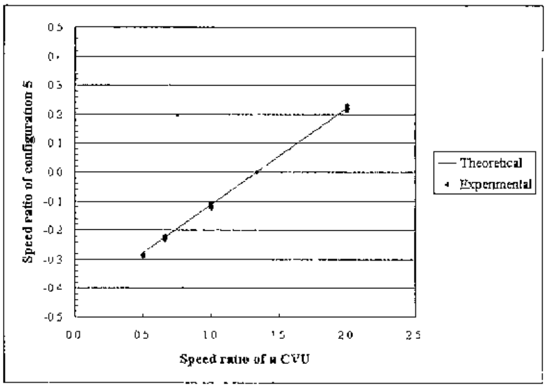


Fig.12(e) Experimental and theoretical speed ratio for a power circulation mode(configuration 5)

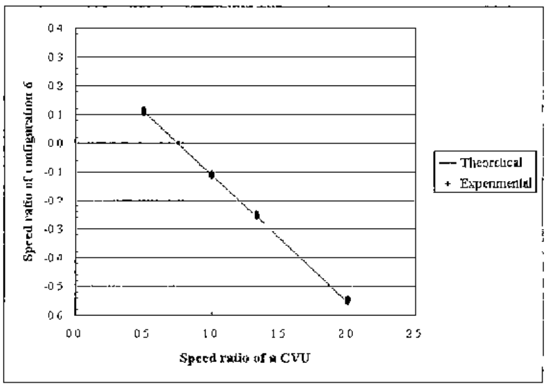


Fig.12(f) Experimental and theoretical speed ratio for a power circulation mode(configuration 6)

Fig.13(a)-(f) are the plots of the overall speed ratio of the CVT versus the speed ratio of a CVU, which show comparisons between the experimental data and the theoretical results for each of the six power split modes. There is no a neutral point and all configurations have an only one-directional motion. It is shown that the experimental results in the each speed ratio of a CVU have the trends similar to the theoretical results. The overall speed ratio of the CVT mechanism having a power split mode may be varied as gear ratios are changed, but it may not generate a neutral point. 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.

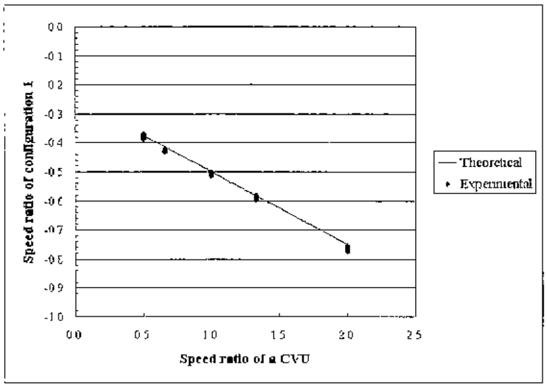


Fig.13(a) Experimental and theoretical speed ratio for a power split mode(configuration 1)

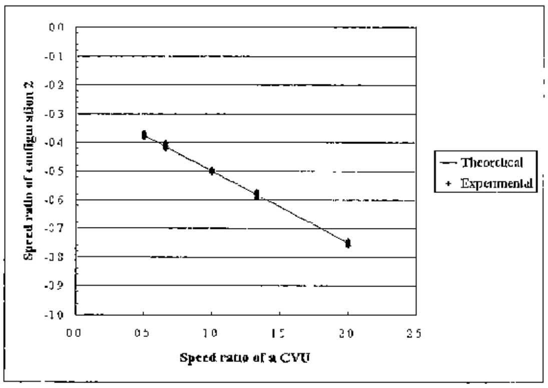


Fig.13(b) Experimental and theoretical speed ratio for a power split mode(configuration 2)

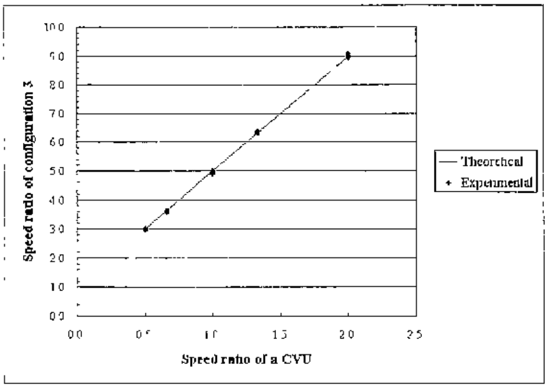


Fig.13(c) Experimental and theoretical speed ratio for a power split mode(configuration 3)

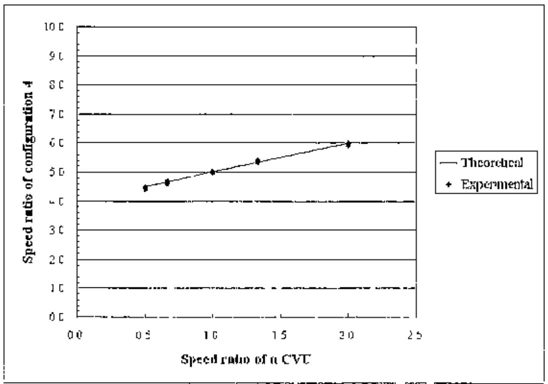


Fig.13(d) Experimental and theoretical speed ratio for a power split mode(configuration 4)

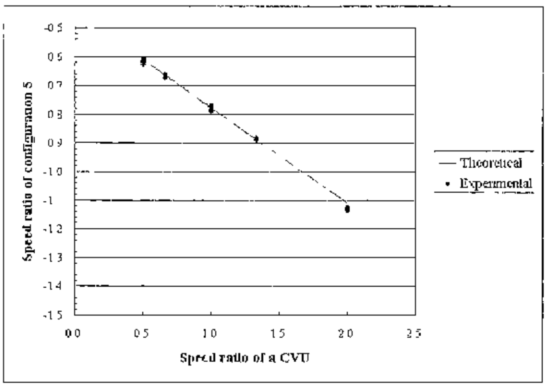


Fig.13(c) Experimental and theoretical speed ratio for a power split mode(configuration 5)

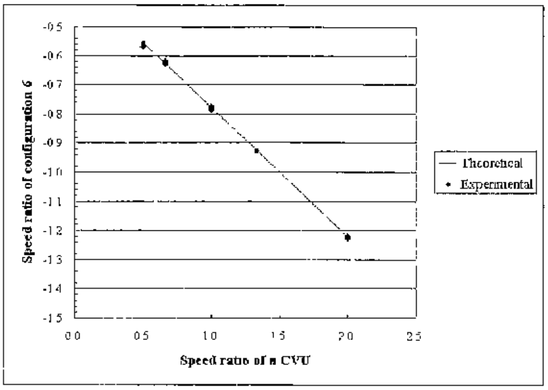


Fig 13(f) Experimental and theoretical speed ratio for a power split mode(configuration 6)

6. Conclusions

The input coupled type CVT considered here is composed of a 2K-H I type differential gear unit and a V-belt type CVU with a variable-diameter pulley. Theoretical relations associated with the overall efficiency and the speed ratio for twelve input coupled type CVT mechanisms, six of them produce a power circulation mode and the others produce a power split mode, have been investigated through experimental studies. From the comparisons between the theoretical results and the experimental results, it has been shown that theoretical relations are valid.

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