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Kinematic Analyses of a Parallel-type Independently Controllable Transmission

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Abstract: This study proposes a novel design of a parallel-type Independently Controllable Transmission (ICT). The parallel-type ICT can produce a continuously variable transmission ratio and a required angular output velocity that can be independently manipulated by a controller yet not affected by the angular velocity of the input shaft. The proposed parallel-type ICT is composed of two planetary gear trains and two transmission-connecting members. A prototype was built to investigate its kinematic characteristics and verify application feasibility.

Keywords: Independently Controllable Transmission (ICT); parallel-type; planetary gear train; transmission-connecting member.

Nomenclature

A	first planetary gear train
AD	one of the rotational shafts of A
AE	one of the rotational shafts of A
B	second planetary gear train
BD	one of the rotational shafts of B
BE	one of the rotational shafts of B
$cmg1$	gear in connecting member
$cmg1D$	gear mounted on $cmsD$
$cmg1E$	gear mounted on $cmsE$
$cmg2$	gear in connecting member
$cmg2D$	gear of D, which is mounted on the shaft coming from A
$cmg2E$	gear of E, which is mounted on the shaft coming from A
$cmg3$	gear in connecting member
$cmg3$	gear of D, which is mounted on the shaft coming from B
$cmg3D$	gear of D, which is mounted on the shaft coming from B
$cmg3E$	gear of E, which is mounted on the shaft coming from B
cms	rotational shaft that $cmg1$ is mounted on
$cmsD$	rotational shaft of D, which is used to connect to the input power source
$cmsE$	rotational shaft of E, which is used to connect to the free-transmission end
CR	shaft connected to the controller
D	first transmission-connecting member
E	second transmission-connecting member
i_0	basic speed-ratio of planetary gear train
i_{0A}	basic speed-ratio of A
i_{0B}	basic speed-ratio of B
n_j	angular velocity and its subscript indicates the rotational shaft
N_j	number of teeth with its subscript indicating the gear
OP	shaft connected to the output power end
pa	carrier member
paA	planet gear carrier of A
paB	planet gear carrier of B
$pp1$	gear of compound planet gear set

*pp*1*A*	gear of compound planet gear set of *A*
*pp*1*B*	gear of compound planet gear set of *B*
*pp*2	gear of compound planet gear set
*pp*2*A*	gear of compound planet gear set of *A*
*pp*2*B*	gear of compound planet gear set of *B*
*ps*1	sun gear
*ps*1*A*	sun gear of *A*
*ps*1*B*	sun gear of *B*
*ps*2	second sun gear
*ps*2*A*	second sun gear of *A*
*ps*2*B*	second sun gear of *B*
*pss*1	rotational shaft on which *ps*1 is mounted
*pss*1*A*	rotational shaft on which *ps*1*A* is mounted
*pss*1*B*	rotational shaft on which *ps*1*B* is mounted
*pss*2	rotational shaft on which *ps*2 is mounted
*pss*2*A*	rotational shaft on which *ps*2*A* is mounted
*pss*2*B*	rotational shaft on which *ps*2*B* is mounted
SD	shaft connected to the input power end
SE	shaft connected to the free-transmission end
α	constant between the rotational shafts
β	constant between the rotational shafts

1. Introduction

In automation engineering applications, it is always desirable to be able to transmit required and suitable power from an energy source to the requesting end. In order for the rotational shaft of the output end to receive appropriate torques and/or angular velocities, workable and efficient power transmission is required between the input and output end. This is generally achieved by means of transmission mechanisms. Continuously variable transmission (CVT) mechanisms, which have a continuous range of transmission ratios and can independently transmit the selected torques, are frequently employed to achieve the optimal power transmission [1].

Various researches and inventions focusing on CVT mechanisms have been proposed for applications. For example, Mantriota designed power split CVT (PS-CVT) systems constituted by the coupling of a CVT, a planetary gear train, and a fixed ratio mechanism [1, 2]. Kim *et al.*, proposed a spherical continuously variable transmission (S-CVT) [3]. Kazerounian and Furu-Szelely presented a parallel disk CVT (PDCVT) consisting of three disks [4]. Imanishi *et al.*, proposed a CVT apparatus that included a toroidal-type CVT, a planetary gear type transmission, and a clutch apparatus [5]. Luo *et al.*, focused on the magnetic belt drive (MBD), in which an additional frictional force between the belt and pulleys was provided by a magnetic belt and magnets [6]. Miller *et al.*, illustrated and described a variable speed transmission having a plurality of tilting balls and opposing input and output discs [7]. Lahr and Hong designed a cam-based infinitely variable transmission of ratcheting drive type [8]. Parrish proposed CVT mechanisms comprising of first and second planetary gear sets [9]. Hsu and Huang presented a systematic methodology to effectively simplify the design of automatic transmissions with parallel-connected epicyclic-types [10]. The aforementioned CVT systems [1-8] included additionally some sliding friction elements, such as rubbing balls, belt-pulley systems, and disks. However, using additional sliding friction elements generally implies that there will be power waste. Therefore, a transmission design, which can provide a controllable power transmission without the need for additional sliding friction elements, is a useful and valuable work.

A novel mechanism with an independently controllable power transmission, referred to as a parallel-type independently controllable transmission (ICT), is proposed in this study [11]. The parallel-type ICT can produce a continuously variable transmission ratio and a required output angular velocity, which is independently controlled by a controller and not affected by the angular velocity of the input power shaft. Such an ICT mechanism can be utilized in, for example, the automatic transmission system of a vehicle or a variable speed wind turbine [12]. The proposed parallel-type ICT is composed of two planetary gear trains and two transmission-connecting members and does not require additional sliding friction elements. To investigate the parallel-type ICT's kinematic characteristics and to demonstrate its application feasibility, a prototype was built and tested.

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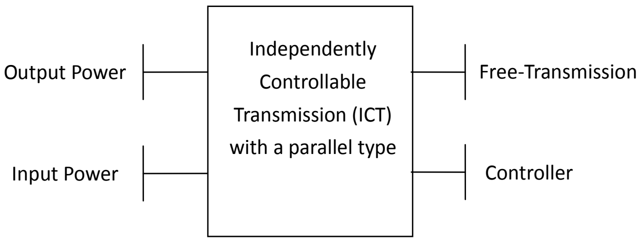

Figure 1. Conceptual scheme of the proposed parallel-type ICT.

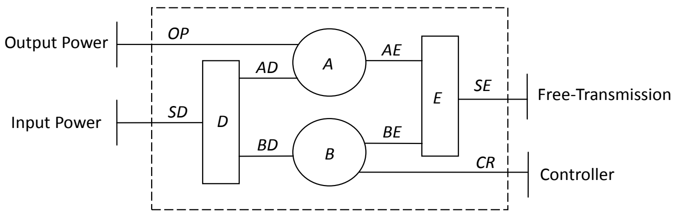

Figure 2. Structure of the parallel-type ICT.

2. Conception and structure of paraleel-type ICT

The conceptual design of the proposed parallel-type ICT as depicted in Figure 1 consists of a mechanism with four rotational shafts, each possessing specific function, i.e., to connect to the input power source, the output power end, the controller, and the free-transmission end. In real-life applications, the input power can be obtained from an engine or a wind turbine, for example. The output end can transmit power to a generator or the wheels of a car. A servo motor whose angular velocity is controllable can serve as the controller. The free-transmission end can be either a second power input or an output, depending on the ICT's configuration and the speed ratio between the input and output shafts. The speed ratio between the output end and the controller is set as a constant and does not depend on the speed of the input shaft. Therefore, the required angular velocity of the output power shaft can be obtained by the independent manipulation of the controller, regardless of the variation in input angular velocity.

The basic structure of the parallel-type ICT, shown in Figure 2, is composed of two planetary gear trains, denoted by *A* and *B*, and two transmission-connecting members, indicated by *D* and *E*. As depicted by *AD*, *OP*, *AE* and *BD*, *CR*, *BE*, each planetary gear train has three rotational shafts, and two of these three shafts connect to the transmission-connecting members *D* and *E*. For example, shafts *AD* and *BD* connect to the transmission-connecting member *D*, and shafts *AE* and *BE* connect to *E*, as shown in Figure 2. By means of shaft *SD*, the transmission-connecting member *D* could connect to the source of input power, whereas the transmission-connecting member *E* could connect to the free-transmission end by shaft *SE*. Finally, the third shaft of the planetary gear train *A*, i.e., *OP*, could connect to the output power end, and the third shaft of *B*, i.e., *CR*, could connect to the controller.

2.1 Establishment of kinematic requirements

To achieve the functions of the proposed ICT mechanism, this study establishes some basic kinematic requirements. First, from the conception described previously, the relationship between the angular velocities of shafts *AD* and *BD*, which are used to transmit the input power to the planetary gear trains *A* and *B*, respectively, can be expressed as

$$n_{BD} = \alpha\, n_{AD} \tag{1}$$

where n denotes the angular velocity of the rotational shaft indicated by its subscript, and α is a constant.
Second, since the angular velocity of the output end is independently manipulated by the controller and not affected by the input angular velocity, the relationship between the angular velocities of the shafts connected to the output end and the controller, i.e., *OP* and *CR*, can be expressed as

$$n_{CR} = \beta\, n_{OP} \tag{2}$$

where β is a constant.

Finally, the relationship between the angular velocities of shafts *AE* and *BE* can be expressed as

$$n_{AE} = n_{BE} \tag{3}$$

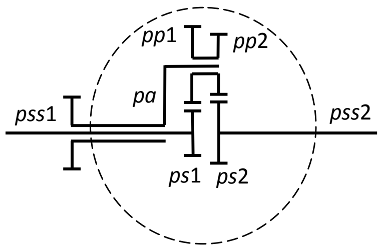

Figure 3. Positive-ratio planetary gear train.

2.2 Positive-ratio planetary gear train

The positive-ratio planetary gear train, shown in Figure 3, is used in the parallel-type ICT. The positive-ratio planetary gear train includes a first sun gear *ps*1 mounted on the rotational shaft *pss*1, a second sun gear *ps*2 mounted on the rotational shaft *pss*2, at least one compound planet gear set that includes gears *pp*1 and *pp*2 and meshes with the first and the second sun gears, and a planet gear carrier *pa*. A positive-ratio planetary gear train means that the shafts of the first and second sun gears, when the carrier is fixed, have the same direction of rotation. Therefore, its basic speed-ratio, which is defined as the ratio of the relative shaft velocities of the first and the second sun gears with respect to the carrier, is consequently positive and cannot be equal to 1 [13]. The shafts of the first sun gear, the second sun gear, and the carrier are the rotational shafts of each planetary gear train in the ICT mechanism, namely *AD*, *OP*, and *AE*, or *BD*, *CR*, and *BE*, as shown in Figure 2, respectively. From the above descriptions, the basic speed-ratio of the positive-ratio planetary gear train, denoted by i_0, can be expressed as

$$i_0 = \frac{n_{pss1} - n_{pa}}{n_{pss2} - n_{pa}} = \frac{N_{pp1} \times N_{ps2}}{N_{ps1} \times N_{pp2}} \tag{4}$$

where *N* is the number of teeth on the gear indicated by its subscript.

By rearranging Equation (4), the following velocity expressions of the rotational shafts *pps*2 and *pa* can be also obtained:

$$n_{pss2} = \frac{n_{pss1} - (1 - i_0) n_{pa}}{i_0} \tag{5}$$

$$n_{pa} = \frac{n_{pss1} - i_0 n_{pss2}}{1 - i_0} \tag{6}$$

2.3 Transmission-connecting member

Figure 4 shows the transmission-connecting member used in this study. The transmission-connecting member comprises gear *cmg*1 mounted on the rotational shaft *cms*, which can be used to connect to the source of input power or the free-transmission end, and gears *cmg*2 and *cmg*3, which are mounted on the shafts coming from the planetary gear trains *A* and *B*, respectively. The function of shaft *cms* is similar to that of shaft *SD* or *SE* shown in Figure 2. The shafts coming from the planetary gear trains *A* and *B* are just the shafts *AD*, *BD* or *AE*, *BE* shown in Figure 2, respectively.

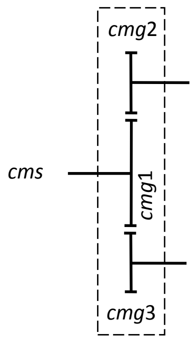

Figure 4. Transmission-connecting member.

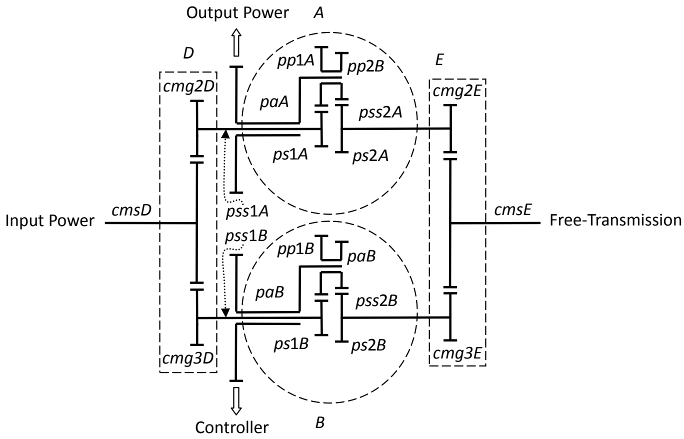

Figure 5. Arrangement of the parallel-type ICT.

3. Kinematic analyses of parallel-type ICT

Based on the kinematic requirements and the structure of the parallel-type ICT as described in previous section, a practical arrangement of the parallel-type ICT, shown schematically in Figure 5, is proposed in this section.

Under this parallel-type ICT structure, both the planetary gear trains *A* and *B* are of the positive-ratio type shown in Figure 3, and the transmission-connecting members *D* and *E* are similar to that shown in Figure 4. Rotational shafts *cmsD* and *cmsE*, similar to shafts *SD* and *SE* shown in Figure 2, are connected to the input power source and the free-transmission end, respectively. Likewise, rotational shafts *paA* and *paB*, similar to shafts *OP* and *CR* shown in Figure 2, are connected to the output power end and the controller, respectively. The function and performance of rotational shafts *pss1A*, *pss2A*, *pss1B*, and *pss2B* will be also similar to those of shafts *AD*, *AE*, *BD*, and *BE*, respectively. From the analyses described previously, Equations (1)-(5) can be rewritten as follows:

$$\frac{n_{pss1B}}{n_{pss1A}} = \frac{N_{cmg2D}}{N_{cmg3D}} = \alpha \tag{7}$$

$$n_{paB} = \beta n_{paA} \tag{8}$$

$$n_{pss2A} = n_{pss2B} \tag{9}$$

$$i_{0A} = \frac{n_{pss1A} - n_{paA}}{n_{pss2A} - n_{paA}} = \frac{N_{pp1A} \times N_{ps2A}}{N_{ps1A} \times N_{pp2A}} \tag{10}$$

$$i_{0B} = \frac{n_{pss1B} - n_{paB}}{n_{pss2B} - n_{paB}} = \frac{N_{pp1B} \times N_{ps2B}}{N_{ps1B} \times N_{pp2B}} \tag{11}$$

$$n_{pss2A}=\frac{n_{pss1A}-(1-i_{0A})n_{paA}}{i_{0A}} \tag{12}$$

$$n_{pss2B}=\frac{n_{pss1B}-(1-i_{0B})n_{paB}}{i_{0B}} \tag{13}$$

where i_{0A} and i_{0B} are the basic speed-ratio of planetary gear trains *A* and *B*, respectively.

Substituting Equations (7) and (8) into Equation (13) yields

$$n_{pss2B}=\frac{\alpha n_{pss1A}-(1-i_{0B})\beta n_{paA}}{i_{0B}} \tag{14}$$

By taking Equation (9) and equating Equations (12) and (14), the design formulas for the parallel-type ICT can be obtained as

$$\begin{cases} i_{0A}=\dfrac{\alpha-\beta}{\alpha(1-\beta)},\ i_{0B}=\dfrac{\alpha-\beta}{1-\beta} & \text{if } \alpha\neq\beta,\ \alpha\neq 1 \text{ and } \beta\neq 1 \\ i_{0A}=i_{0B} & \text{if } \alpha=\beta=1 \end{cases} \tag{15}$$

Finally, according to Equation (9), it can be concluded that

$$N_{cmg2E}=N_{cmg3E} \tag{16}$$

4. Demonstrations of ICT prototype

In this section, a prototype of the proposed ICT mechanism, which is shown in Figure 6, is built to investigate its kinematic characteristics and to demonstrate the validity of the design formulas and the application feasibility.

For this ICT prototype, the constants shown in Equations (7) and (8) are chosen to be α=1.5 and β=2. From Equation (15), the basic speed-ratio of planetary gear trains *A* is $i_{0A}=1/3$, and the basic speed-ratio of planetary gear train B is $i_{0B}=0.5$. Based on the relationships shown in Equations (7), (10), (11), and (16), the number of teeth for each gear used in this prototype can be chosen and listed in Table 1.

Figure 7 shows an experimental test-bed of the ICT prototype, and Figure 8 is a plot of the experimentally obtained angular velocities of the rotational shafts, including the input power, the output power, the controller, and the free-transmission end shafts. As the constant β is set equal to 2, it can be observed that the magnitude of the angular velocities of the controller shaft, which is depicted by the green dash line, is twice that of the output power shaft, which is depicted by the red solid line. It can be also observed that the controller can independently control the angular output velocities, regardless of the variation of the angular velocity of the input power shaft as depicted by a blue dash-dot line.

Table 1. Number of teeth for each gear used in ICT prototype.

Gear	*cmg1D*	*cmg2D*	*cmg3D*	*cmg1E*	*cmg2E*
Teeth number	60	60	40	60	50
Gear	*cmg3E*	*ps1A*	*ps2A*	*pp1A*	*pp2A*
Teeth number	50	45	30	15	30
Gear	*ps1B*	*ps2B*	*pp1B*	*pp2B*	
Teeth number	40	30	20	30	

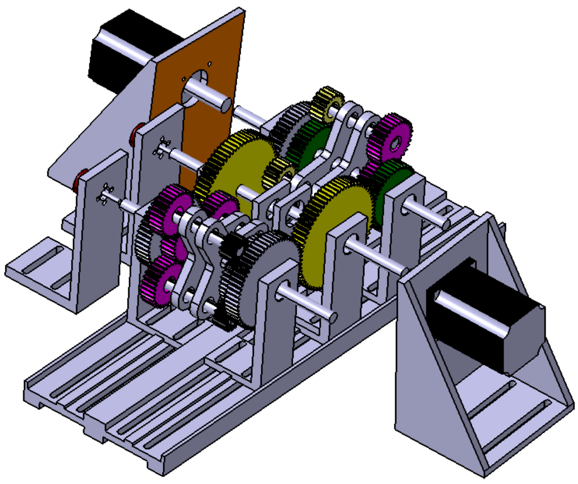

Figure 6. ICT prototype.

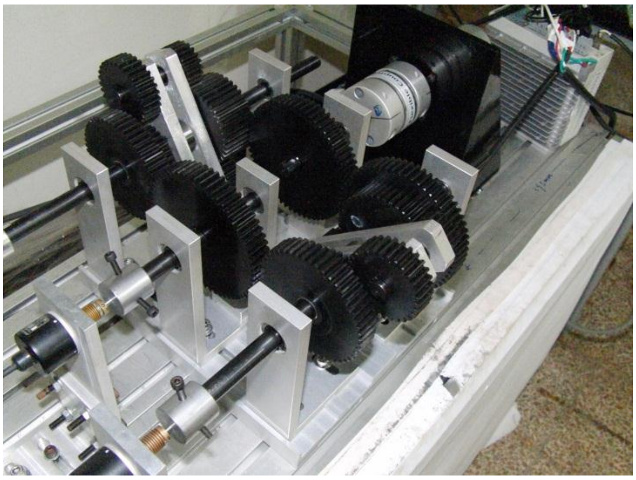

Figure 7. A test-bed of ICT prototype.

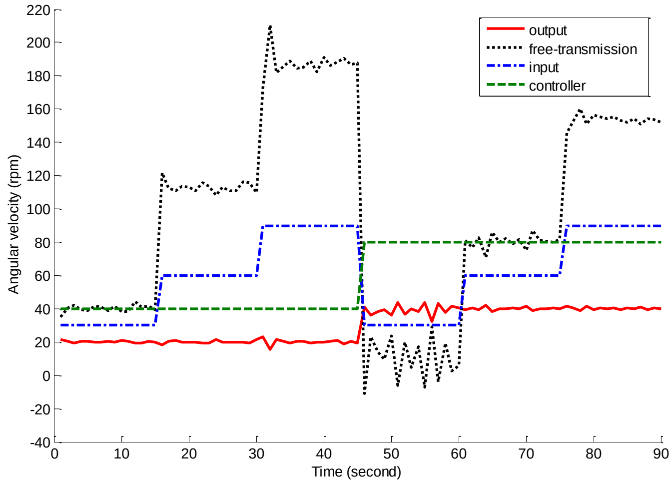

Figure 8. Angular velocities of the ICT mechanism's rotational shafts.

5. Conclusion

In this study, a novel parallel-type ICT is proposed. The kinematic characteristics of this proposed design are investigated, and the validity of the design formulas is verified. To demonstrate the application feasibility, a prototype of the parallel-type ICT is built and tested. Because the ICT mechanism can produce the required angular velocity at the output power shaft, which is not affected by the input angular velocity, and provide infinitely and continuously variable transmission by independently manipulated the controller, such an ICT mechanism could be applied to variable speed wind turbines and automatic transmission systems of vehicles. Further research into the dynamic performance and the applications of the ICT mechanisms are proceeding.

Acknowledgment

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