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# APPLICATION OF DISC SPRING IN CLAMPING FORCE MECHANISM FOR ELECTRO-MECHANICAL CONTINUOUSLY VARIABLE TRANSMISSION

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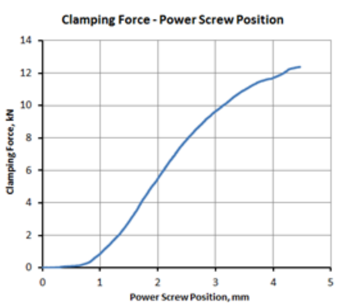
## Graphical abstract




## Abstract

Pulley-based continuously variable transmission (CVT) with metal pushing V-belt (V-belt) offers tremendous potentials in the fuel economy of the car due to its wide and continuous ratio coverage. Nevertheless, the existing pulley-based CVTs in automotive markets use electro-hydro-mechanical (EHM) actuation system to vary its ratio and to provide sufficient clamping force on the V-belt. This, unfortunately, leads to a significant high power consumption from the engine of the car which eventually worsens the car's fuel economy. To address this issue, researchers introduce electro-mechanical CVT (EM CVT) in which the application of the EHM actuation system is replaced by an electro-mechanical (EM) actuation system. This paper discusses the application of disc spring in clamping force mechanism of EM CVT. The selected disc spring is analyzed and evaluated to prove its workability for CVT's application. The analysis results indicate that the application of disc spring in clamping force mechanism of EM CVT is possible and it also offers some benefits particularly in term of its compact design.

Keywords: Continuously variable transmission, electro-mechanical, disc spring, dual acting pulley, metal pushing V-belt



## 1.0 INTRODUCTION

In recent years, due to the volatility of fuel's price in the markets plus the increasing cost of living, the issue of car's fuel economy is becoming increasingly important for many drivers. To address this issue, most car manufacturers have put their focus on developing an efficient automotive transmission and one of the outcomes from their efforts is a pulley-based continuously variable transmission (CVT).

Generally, the main role of an automotive transmission is to transfer torque from car's engine to its wheels. To perform this, a pulley-based CVT does not use a set of discrete gears. Instead, the torque is transferred from the primary pulley (connected to the engine) to the secondary pulley (connected to the wheels) through the application of a metal pushing V-belt (V-belt). In order to achieve this, a sufficient clamping force on the V-belt is required.

Sufficient clamping force on the pulley produces a normal force which results in traction force between a V-belt's element and the pulley [1,2]. As a result, the V-belt will rotate with the same speed as the primary and the secondary pulleys, allowing the torque to be transferred from the primary pulley to the secondary pulley. However, insufficient clamping force causes an excessive slipping of the V-belt and this reduces the total lifespan of the CVT's components in a long run while at the same time leads to its inefficiency [3,4]. To avoid this, the clamping force is usually set by the manufacturers at about 30% more than required for normal operation [3]. This, however, is also not so desirable since it also leads to CVT's inefficiency due to the excessive friction force between the components of the V-belt [5,6]. Not only that, it also causes high power consumption from the car's engine due to the requirement of continuous hydraulic pressure to maintain the clamping force [4,5,6]. Therefore, to address these issues, some researchers have explored a novel idea of replacing the application of the existing EHM system for the clamping force with an electro-mechanical (EM) system in a pulley-based CVT (EM CVT).

## 2.0 CLAMPING FORCE MECHANISM IN EM CVT

The introduction of EM CVT is intended to overcome the issue of engine's high power consumption to maintain a constant CVT ratio and the required clamping force. In EM CVT, the axial movement of CVT's pulleys is actuated through the EM system without the application of a hydraulic pump. Once the desired CVT ratio and clamping force is reached, pulley's position is maintained through a mechanical self-lock mechanism. As a result, the requirement of continuous hydraulic pressure for maintaining the clamping force can be eliminated. Until this moment, there are several concepts and prototypes of the pulley-based CVTs with EM actuation system that were already developed and tested by researchers globally. Some of the notable examples of pulley-based CVT with EM system are ElectroMechanical Pulley Actuation CVT (EMPACT CVT) by Technische Universiteit Eindhoven and Electro-Mechanical Controlled CVT (EMCCVT) by Aichi Machine Industry.

EMPACT CVT uses double epycyclic gears, spindle nut and two servomotors; the primary and the secondary DC motors, to axially move the primary and the secondary pulleys simultaneously in the opposite direction during the changing of CVT ratio [4,7. According to [4]Klaassen (2007), EMPACT CVT has a CVT ratio range from 2.00 (maximum underdrive) to 0.48 (maximum overdrive). In this prototype, the clamping force is controlled on its secondary pulley through the secondary DC motor that is connected to its secondary pulley's pull rod through the clamping force adjustment ring gear. Then, the clamping force and the desired CVT ratio are maintained through its spindle self-lock mechanism. There is no apparent indication that this prototype uses any spring in its clamping force mechanism. Thus, EMPACT CVT could potentially eliminate losses during spring's compression and release. Nevertheless, it needs an additional controller for its secondary DC motor to control CVT ratio and clamping force.

EMCCVT, on the other hand, is developed by Aichi Machine Industry and is reviewed previously by Xinhua, et al., (2008) [8]. It uses a combination of geartrain and a dry hybrid V-belt for transferring the torque. In a dry hybrid V-belt, the bands of the hybrid V-belt are made of aramid fibers and rubbers instead of metal [9]. Here, the CVT ratio is varied by using an actuator motor and a spindle on the primary pulley. The desired CVT ratio and clamping force is retained through the spindle. Once the primary pulley's movable sheave is axially moved, the axial position of the secondary pulley's movable sheave will be adjusted accordingly due to mechanical linkage through the hybrid V-belt. During the underdrive ratio, engine's torque is transferred through EMCCT's hybrid V-belt and geartrain. Once it reaches overdrive ratio, the torque that is transferred through the geartrain will be cut off due to the application of 2-way-clutch. Hence, the torque is now transferred only through the hybrid V-belt.

The clamping force mechanism of EMCCVT uses compression spring and torque cam, therefore the issue of high clamping force during the overdrive ratio is inevitable. In addition, the loss during spring's compression and release is also unavoidable. Nevertheless, unlike EMPACT CVT EMCCVT requires no additional controller for its clamping force mechanism.

## 3.0 DISC SPRING IN CLAMPING FORCE MECHANISM OF EM CVT

### 3.1 Electro-Mechanical Dual Acting Pulley CVT

Electro-Mechanical Dual Acting Pulley (EMDAP) CVT uses power screw mechanisms and two DC electric motors (primary and secondary DC motor) to actuate the axial movement of the primary and the secondary pulleys during the process of changing the CVT ratio [10]. It has a CVT ratio range from 2.00 (maximum underdrive) to 0.70 (maximum overdrive). Once the desired CVT ratio is reached, both motors will stop operating and the position of the pulleys is retained through the design of the thread in the power screw mechanism. Hence, no extra and continuous power from the car's engine is required to maintain the CVT ratio and the clamping force. In addition to that, the prototype of EMDAP CVT also features dual acting pulley system, unlike most of the automotive pulley-based CVTs that use a single acting pulley system. This system allows both sides of the pulley sheaves to be moved axially during the process of changing the CVT ratio.

EMDAP CVT's clamping force mechanism uses two disc springs (also called Belleville spring) on its secondary pulley to continuously providing clamping force on the V-belt during the process of changing the CVT ratio[11]. The deflection of these disc springs is controlled by the secondary DC motor. However, it is a bit difficult to effectively control the clamping force due to the requirement of an additional clamping force controller in the secondary DC motor[11].

### 3.2 Electro-Mechanical Dual Acting Pulley CVT with Independent Clamping Force Actuator

The new design of EMDAP CVT with independent clamping force actuator (EMDAP-ICFA CVT) is developed as a continuation from the previously described EMDAP CVT. Figure 1 shows the schematic diagram of EMDAP-ICFA CVT [12,13]. It still uses dual acting pulley system and power screw mechanism, just like EMDAP CVT, to actuate both its primary and secondary pulleys. However, unlike its predecessor, it has a CVT ratio range from 3.00 (maximum underdrive) to 0.60 (maximum overdrive). Not only that, in EMDAP-ICFA CVT, only the primary DC motor is responsible for changing the CVT ratio. The inclusion of middle gears in its design allows the torque from the primary DC motor to be transferred simultaneously to the secondary pulley mechanism during the event of changing the CVT ratio.

Another important new feature of EMDAP-ICFA CVT is the new clamping force mechanism called independent clamping force actuator (ICFA) system. Similar to the existing EMDAP CVT, there are also two disc springs in ICFA system to ensure continuous clamping force on the V-belt during CVT ratio changing process. ICFA system allows the clamping force on the V-belt to be adjusted accordingly whenever required through the secondary DC motor. This offers a much simpler possibility to control the sufficient clamping force on the CVT's V-belt. The schematic diagram of ICFA system is highlighted in Figure 2 [12].

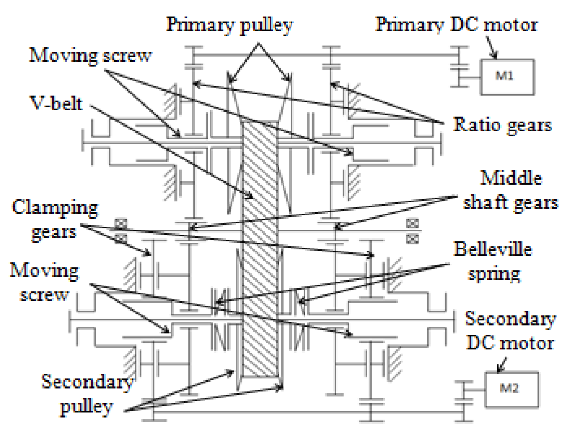



**Figure 1** Schematic diagram of EMDAP-ICFA CVT

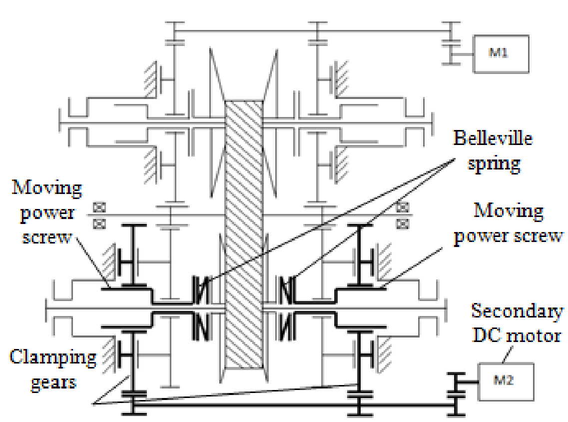



**Figure 2** Schematic diagram highlighting ICFA system

### 3.3 Specifications of the Disc Spring

The selected disc spring (also called Belleville spring) for application in EMDAP CVT and EMDAP-ICFA CVT is DIN 2093-C112 which has a maximum spring force of around 11kN (Figure 3). Unlike compression spring, a disc spring offers significantly high spring's force with a much smaller deflection. Due to this feature, researchers from Universiti Teknologi Malaysia are exploring and studying the possibility to apply it in EMDAP CVT and EMDAP-ICFA CVT[10]. Until this moment, there are still limited researches done on this area.

**Figure 3** Disc spring DIN 2093-C112

According to Supriyo (2011) [14], this specification is suitable for application in a CVT for a 1.6L gasoline engine. The disc spring DIN 2093-C112 has an outer diameter of 112mm, inner diameter of 57mm and a thickness of 3mm. It has a maximum deflection of 3.9mm. Graph in Figure 4 shows the characteristic of the selected disc spring's force vs deflection according to the specifications provided by Wittel et al., (2011) [15].

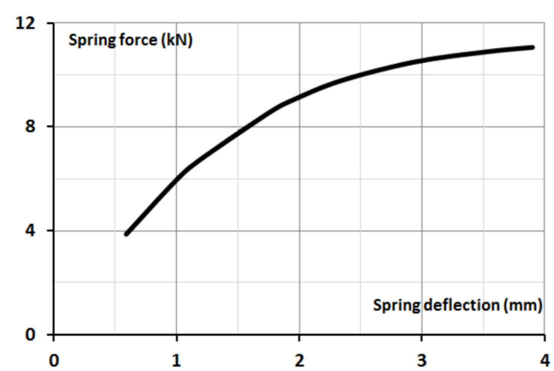



**Figure 4** Spring force vs deflection of disc spring DIN 2093-C112

## 4.0 EXPERIMENTAL STUDY OF INDEPENDENT CLAMPING FORCE ACTUATOR (ICFA) SYSTEM

### 4.1 ICFA System

The main objective in developing ICFA system is to allow the adjustment of clamping force on the V-belt whenever required. In this system, the adjustment of clamping force is achieved by changing the deflection of the disc spring on EMDAP-ICFA CVT's secondary pulley through sufficient torque transferred by the secondary DC motor. The torque from the secondary DC motor is multiplied through a gear reducer with a ratio of 1:30 to the pinion shaft. The pinion shaft is then connected to the moving power screw through pinion gears and clamping gears. The clamping gear and the power screw are connected through dowel pins and the outer thread of the power screw is meshed with the inner thread of ratio gear. Because of this thread, a rotational motion of clamping gear is translated into the axial movement of the power screw. Then, the disc spring is deflected accordingly, results in changes of spring force (FSpring) which is equals to the clamping force (FC) on the V-belt. The relationship between the torque from the secondary DC motor (TM) and the clamping force (FC) on the V-belt is explained in the mathematical equation 2. In this mathematical equation, iGR represents the ratio of the secondary DC motor's gear reducer, iCG represent ratio of the clamping gear to pinion gear, dPS represents the mean diameter of the moving power screw's outer thread (dPS equals to 85.51mm), L is the lead of the moving power screw's thread and μ is the friction coefficient on the contact between the moving power screw (L equals to 2mm) and the clamping gear (μ equals to 0.16). iCG is derived from the mathematical equation 3, with NCG and NPG represent the number of teeth of the clamping gear and the pinion gear respectively. In ICFA system, NCG and NPG equal to 72 and 14 respectively, which results in iCG equals to 5.14. An overview of ICFA system is shown in Figure 5.

$$F_{Spring} = F_C \tag{1}$$

$$F_C = i_{GR} i_{CG} T_{SM} \left( \frac{2}{d_{PS}} \right) \left( \frac{\pi d_{PS} - \mu L}{L + \mu \pi d_{PS}} \right) \tag{2}$$

$$i_{CG} = \frac{N_{CG}}{N_{PG}} \tag{3}$$

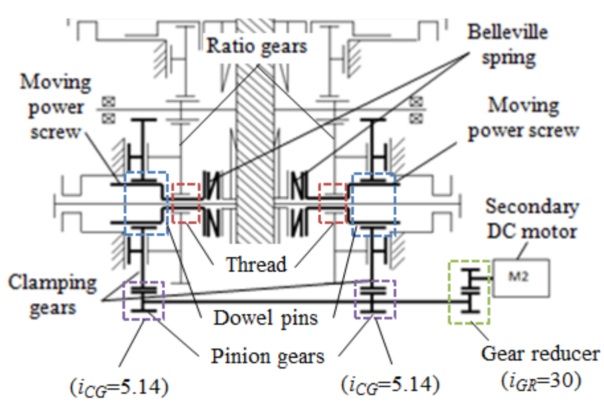



**Figure 5** Overview of ICFA system

As suggested by Supriyo [10], the required clamping force on the V-belt ranges around 10kN on each side of the V-belt, hence the total clamping force on the V-belt is 20kN. Therefore, in order to realize this amount of clamping force, the torque required from the secondary DC motor is 0.93Nm based on the mathematical equations 1, 2 and 3. Nevertheless, a higher clamping force is also possible as long as the disc spring is still within its deflection range and the DC motor is still capable of transferring a higher torque.

## 4.2 Experimental Setup

The prototype of ICFA is developed to evaluate its workability and also to study the actual deflection force of the selected disc spring (Figure 6). The experimental setup is shown in Figure 7. In this experimental setup, deflection of the disc spring in the clamping force mechanism is adjusted by using a brushless DC motor (BLDC motor) with a rated torque of 1.177Nm at 3000rpm [14. The BLDC motor is controlled through its manual controller and it is connected to the moving power screws through pinion shaft and clamping gears. Once sufficient torque is provided by the DC motor, the moving power screws will be moved axially. This results in change of the disc spring's deflection, which causes changes in the disc spring's force.


**Figure 6** Prototype of EMDAP-ICFA CVT

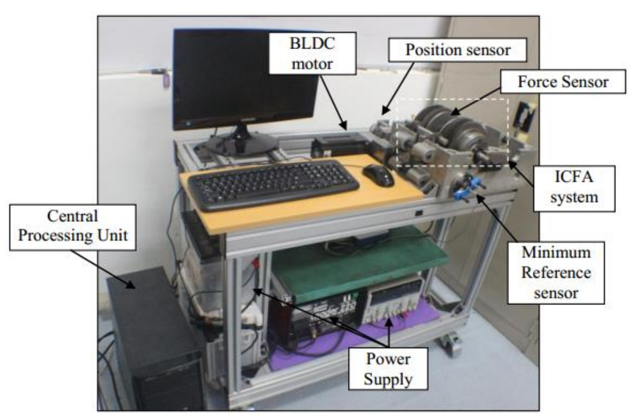



**Figure 7** Experimental setup for ICFA system

To measure the actual clamping force from the pulley that is resulted from the deflection force of the spring, a force sensor (LC8300 of Omega Eng) is positioned between the pulley sheaves (Figure 8). This sensor is set to read the force of up to 22kN and gives 5V of signal voltage with the help of DMD4059 amplifier. During the experiment, axial movement of the power screw results only in a change of the disc spring's deflection state, while the positions of the pulley sheaves and the force sensor remain unchanged.

In ICFA system on the experimental setup, the deflection of disc spring is equivalent to the axial movement of the power screw. 2mm of the power screw's axial movement is translated from 1 rotation of clamping gear. The clamping gear is connected to the BLDC motor's pinion shaft through a pinion gear with the ratio of 72:14. Therefore, in ICFA system, 1 rotation of pinion shaft equals to 0.389mm deflection of spring. Hence, to measure the actual deflection of the disc spring, a position sensor (Omron rotary encoder) is attached to the BLDC motor's pinion shaft (Figure 9) together with the minimum reference sensor (Figure 10). The minimum reference sensor (inductive proximity sensor) is used to indicate the starting point to measure the deflection of the spring.

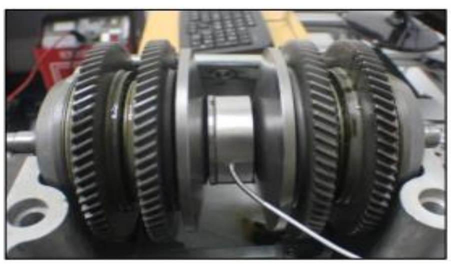


**Figure 8** Position of the force sensor between the pulley sheaves

**Figure 9** Omron rotary encoder attached to BLDC motor's pinion shaft

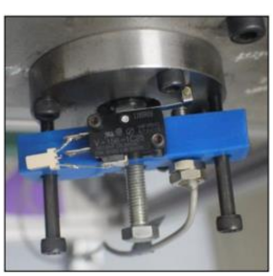


**Figure 10** Minimum reference sensor attached to BLCD motor's pinion shaft

## 4.3 Results and Discussions

The result of the experimental study on the clamping force of ICFA system is produced as a graph of clamping force vs power screw's axial position in Figure 11. Generally, the clamping force in the graph is equivalent to the disc spring's deflection force since the force that is measured by the force sensor comes from the deflection of the disc spring through the pulley sheaves. The graph shows that the maximum clamping force is around 12kN instead of the total clamping force of around 20kN and this is due to the design of the experimental setup. This experiment is designed in such a way that ICFA system is prepared on the test rig similar with its actual operational condition in EMDAP-ICFA CVT. This results in a clamping force flow illustrated in Figure 12. When the torque is produced by the BLDC motor, both disc springs that are position on the left and right of the force sensor will be deflected simultaneously with a same deflection (∆XLeft and ∆XRight). Thus, the clamping force from the left disc spring will act as a reaction force of the right disc spring's clamping force or viceversa. As a result, the clamping force that is measured by the force sensor is equivalent to only one disc spring's deflection. Therefore, as far as the clamping force is concern, this experiment result is still consistent with the selected disc spring specifications.

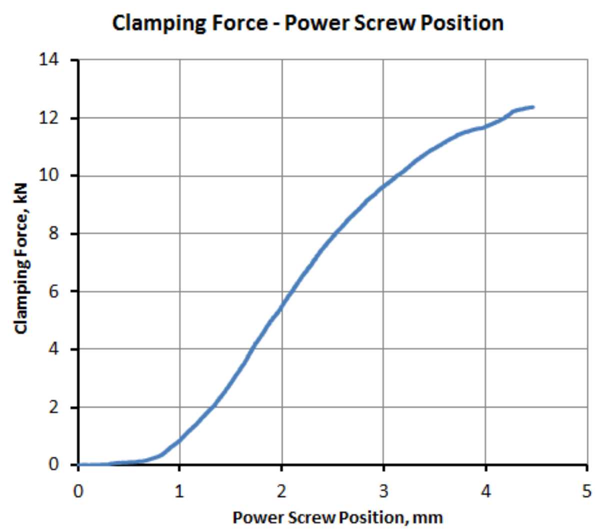



**Figure 11** Graph of clamping force – power screw position obtained from the experiment

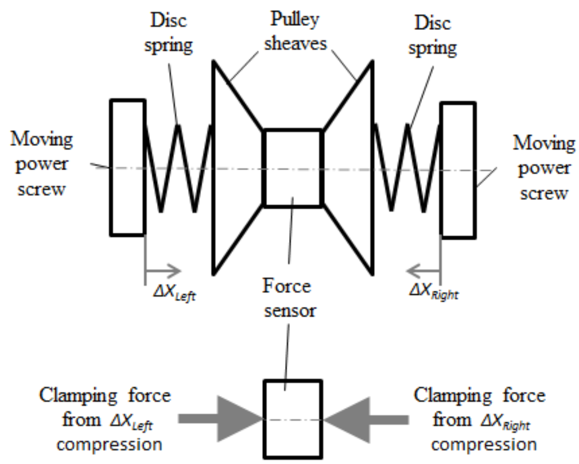



**Figure 12** Clamping force flow from the deflection of the disc spring

However, the graph also shows that the range of the moving power screw's axial position is significantly wider the selected disc spring's deflection range. From the graph, the maximum axial displacement of the moving power screw is around 4.5mm which is around 0.6mm more than the rated maximum deflection of the selected disc spring DIN 2093-C112. One of the likely reasons is due to a small tolerance between the force sensor and the pulley sheaves. This explains the very slow increase in the clamping force in the range of power screw's position from 0mm to circa 0.7mm. Another possible reason is the tolerances of the disc spring itself, which according to a number of disc spring's manufacturer can lead to an additional deflection range of up to 0.2mm 16,17]. Therefore, it is estimated that the actual start point of the disc spring's deflection is somewhere within the range of the power screw axial position from 0mm to 1mm.

In addition, the graph also shows higher maximum clamping force of more than 12kN at the maximum power screw axial position as compared to the disc spring's rated maximum deflection force of around 11kN. According to the handbooks by disc spring's manufacturers SPIROL International Corporation (2013) and Adolf Schnorr GmbH + Co. KG (2003),[16,17] this is possible due to the shorten force moment arm because of the significant deflection of the disc spring. As a result, in order to further deflect the disc spring, a higher deflection force is required. However, this is generally advantageous for application in ICFA system since higher clamping force can be exerted on the V-belt which allows higher torque to be transferred from the car's engine to the wheels.

## 5.0 CONCLUSION

As a conclusion, the new design of EMDAP-ICFA CVT holds tremendous potentials for automotive application since it offers the advantages of EM CVT. ICFA system features in this new design also offers a much simpler option to control the clamping force as compared to the previous design of EMDAP CVT.

An experimental study is carried out to study the workability of ICFA system and also the suitability of the selected disc spring for application in ICFA system. From the experiment, generally it is proved that the design of ICFA system is workable. The selected disc spring of DIN 2093 C112 is evaluated and it is capable to handle the clamping force of up to 12kN, which is suitable for application in a CVT for a 1.6L gasoline engine[14]. Furthermore, with the application of disc spring in ICFA system, its advantage in term of compactness can be reaped.

Nevertheless, this experiment suggests that more precise measurement of the disc spring's deflection is desirable. In ICFA system, the deflection of disc spring is only measurable through the rotation of the pinion shaft as explained in the previous chapter 4.1. Although this approach is workable, its precision can still be improved further. For future works, it is sensible to concentrate on the possible controllers that can be used for the clamping force before on-the-road testing of EMDAP-ICFA CVT can be performed.

## Acknowledgement

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