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The singular point transition concept: A novel continuously variable transmission comprising planetary gear trains and a variator

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ABSTRACT

The singular point transition concept relates a novel type of continuously variable transmission. This transmission comprises a pair of planetary gear trains and a couple of electric motors, used to control the overall speed ratio. Its singularity lies in the topology of operation, with less than 10% of nominal power circulating through the electric path. This low power level is achieved by segmenting the range of operation of the transmission.

To validate this technology, a test bed was built. The transmission presented here is able to provide any output/input speed ratio within the interval of 0:1.55, meaning that it also offers the function of an infinite variable transmission. Description of the system and results of experimental tests are presented. The results showed that the transmission is able to function in the whole range of operation. They also showed that under load conditions the fraction of power transmitted through the electric path is maintained around the design value.

1. Introduction

There are various types of continuously variable transmissions (CVTs), with conical and fluids systems being the more common. However, there are other types that are based on gears. To achieve a continuous variation, these transmissions take advantage of the characteristic of operation of planetary gear trains (PGTs). Although various configurations have been proposed, we are referring specifically to those comprising a pair of PGTs. In the academic scenario some examples can be seen in [1–3], and concerning patents some can be seen in [4,5]. The particular characteristic of these systems is that two shafts of the PGTs of the mechanism are interconnected creating an electric or a mechanical path between them. The components comprising this path are used to obtain a continuous control of speed. Two configurations can be found in this path: one with an energy source half way or another with a free way between the two shafts. The first case corresponds to a hybrid transmission, where the energy source acts also as a storage system. This configuration, whose path will be termed here as the hybridised path, allows the use of only one shaft at the time or both simultaneously, providing or withdrawing energy. The second configuration corresponds to not-hybridised CVTs, where power taken from a shaft is directly transmitted to the other, while simultaneously controlling the overall speed of the transmission. On CVTs with this configuration, as the one presented in this article, the element contained in the path is termed as the variator. Depending on the configuration of the mechanism, a higher or lower fraction of the power is transmitted through the variator. If a high fraction is transmitted, the design is challenged to find a suitable system. Using a hydraulic system implies high efficiency penalty. The use of a mechanical CVT or a pair of motors turns into an unsuitable option as the amount of power is increased. Therefore, in this kind of CVTs, there is interest in reducing as much as possible the amount of power being transmitted through the variator. However, the amount of power being transmitted has a limit depending on the construction of the mechanism and the range of overall speed ratio to be provided by the CVT (minimum speed ratio:maximum speed ratio). Once the topology of the connections of the PGTs is defined, there is a limit below which it is not possible to further reduce the fraction of power circulating in the variator. To this respect, the present work proposes a solution to reduce the amount of power of this element by combining a CVT with a number of speed gears. Hence, the speed ratio range of the CVT is fractioned and as consequence the range at each speed gear is reduced; accordingly reducing the amount of power of the variator as well. The complete speed ratio range of the CVT remains

Abbreviations: CVT, continuously variable transmission; IVT, infinite variable transmission; PGT, planetary gear train; DOF, degree of freedom.

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Nomenclature

Symbols

ω_{m1}, ω_{m2}	angular velocities of motor 1 and 2
ω_{in} and ω_{out}	angular velocities of input and output
k	gear ratio between teeth of the PGT
GR_{m1}, GR_{m2}	gear ratios between motor and each corresponding shaft
ω_{max_motor1}	maximum angular velocities of motor 1
ω_{max_motor2}	maximum angular velocities of motor 2
τ	overall speed ratio of the CVT

high because of the consecutive action of the different speed gears. Some mechanisms that follow these criteria have been proposed, such as patents US 5643121 [6] and US 6595884 [7].

The current article explains the mechanism based on the patent WO/2005/078315 [8], which deals with a transmission able to operate with a continuous variation of speed ratio. In particular, this CVT is thought as an option to replace hydraulic CVTs like those installed in a forklift with an internal combustion engine. In line with this, the transmission presented also offers the function of an infinite variable transmission (IVT).

The configuration and testing of an experimental test bed is explained, and the results of various tests are shown, allowing the validation of the concept with a functioning transmission.

2. The CVT

2.1. The concept of the CVT

The development of this transmission is based on the patent WO/2005/078315 [8]. This patent relates a transmission comprising two PGTs interconnected in such a way that a mechanism with continuous variation of speed ratio is achieved. Fig. 1 presents the scheme of the transmission with this configuration. The squares with discontinuous lines correspond to PGTs with two degrees-of-freedom (DOFs). Sun and planet gears of each PGT are interconnected one to the other. The rectangular boxes shown midway represent fixed geared steps, which are used to extend the range of the transmission. A total of eight sequential gear ratios are available, four on each connecting branch. The engine would be connected to the input side and the vehicle to the output.

The DOFs of the mechanism are further reduced by interconnecting two of the shafts of the transmission. To produce a CVT, the speed ratio of this connection must vary in a continuous way. The variator could be a CVT of any type; however, this transmission does the variation with electrical means, using two electric motors. Fig. 2 displays this concept: by controlling the operation of the electric motors, the speed ratio of the whole transmission can be controlled.

It is noticeable that some transmissions, such as the one presented by Grewe et al. [9] of general motors (GM), have presented designs also based on the utilisation of two PTGs, in which one of them can be blocked and the output speed is regulated using an electric motor, effectively making a CVT. This is an outstanding example of the potential and flexibility when using a PGT. However, since the CVT of GM has a hybridised path, having energy flow to and from a secondary electrical energy source/storage system, in this case electrical batteries are required. In contrast, in the CVT presented in this article, the utilisation of two electric motors has been predominantly based on technical advantages. During the design stage, focus was placed in reducing the power in the variator. It was downsized to such level that it was found recommendable to use electrical machines instead of a mechanical or hydraulic CVT. Using a mechanical system would have required the implementation of an additional speed control system, adding complexity. In contrast, in electric motors speed measurement is not complex and so they facilitate a simultaneous speed and power flow regulation.

For this CVT, the motors are connected between the ring and the sun of the input PGT. Fig. 3 displays a scheme of the transmission.

Considering this configuration, the speeds of motors 1, 2 and input (ω_{m1}, ω_{m2} and ω_{in}) are correlated with the equation:

$$\omega_{in} = k \cdot GR_{m1} \cdot \omega_{m1} + (1-k) \cdot GR_{m2} \cdot \omega_{m2} \quad (1)$$

where k is the gear ratio between teeth of the PGT, whereas GR_{m1} and GR_{m2} are the gear ratios between each motor and the corresponding shaft to which it is connected.

During operation, the maximum speed motor 1 is able to spin occurs when motor 2 is standing still, which means that:

$$\omega_{max\_motor1} = \frac{\omega_{in}}{k \cdot GR_{m1}} \quad (2)$$

Analogously, for motor 2 it is:

$$\omega_{max\_motor2} = \frac{\omega_{in}}{(1-k) \cdot GR_{m2}} \quad (3)$$

This implies that for each motor the maximum speed is also function of the input speed. This characteristic is important to explain the operation of the system because it allows having any speed in the input as long as the motors rotate within operating conditions.

Fig. 3 also shows the structure of the fixed gear steps with regard to the PGTs. The inter-connection of these elements is achieved

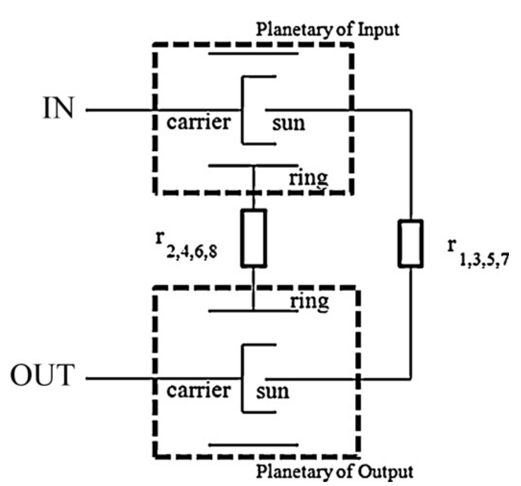

Fig. 1. Scheme of the CVT with two degrees of freedom.

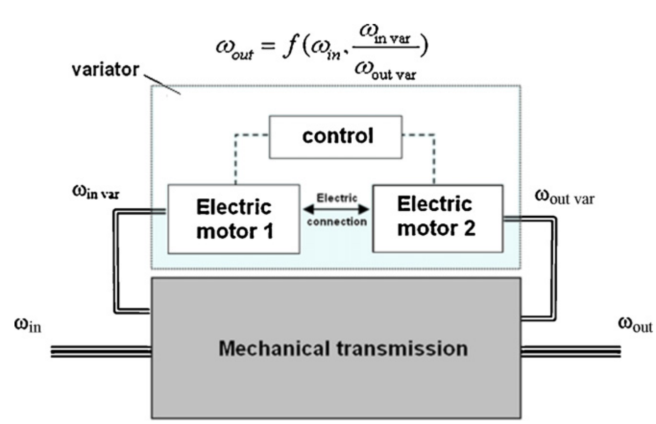

Fig. 2. Control of the CVT using two electric motors. $\omega_{in\ var}$ and $\omega_{out\ var}$ = speed in electric motors, ω_{in} and ω_{out} = input and output speed of transmission.

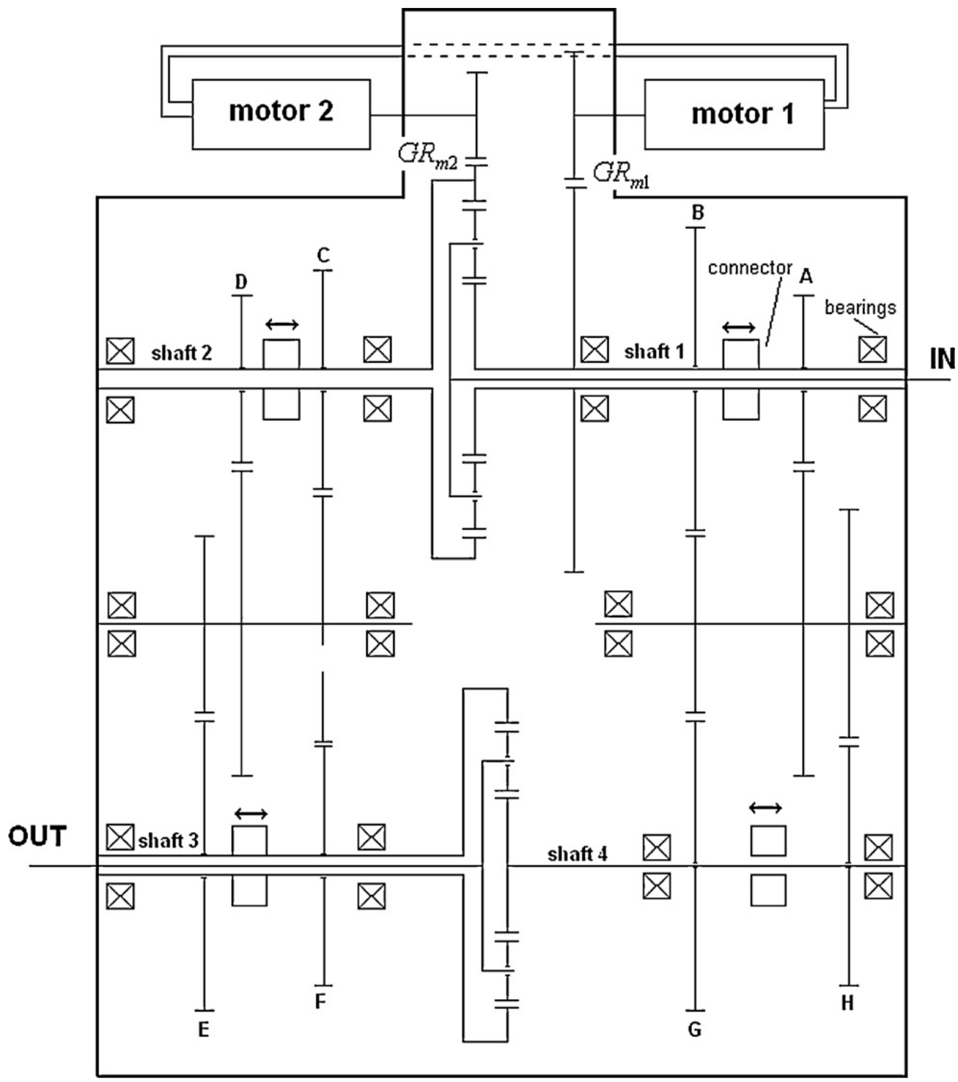

Fig. 3. Scheme of CVT configuration.

using connectors. These connectors can link one, and only one, of the fixed gears to its respective PGT. For example: the connector located in shaft 2, termed connector 2 (the number of each connector corresponds to the shaft in which it operates), which is joined mechanically to the ring of the input PGT, can connect this shaft with either gear C or gear D, whereas connector 3 can connect shaft 3 to either gear E or gear F. The gears A to H are all floating, thus they will be operating only when a connector is linking them to its

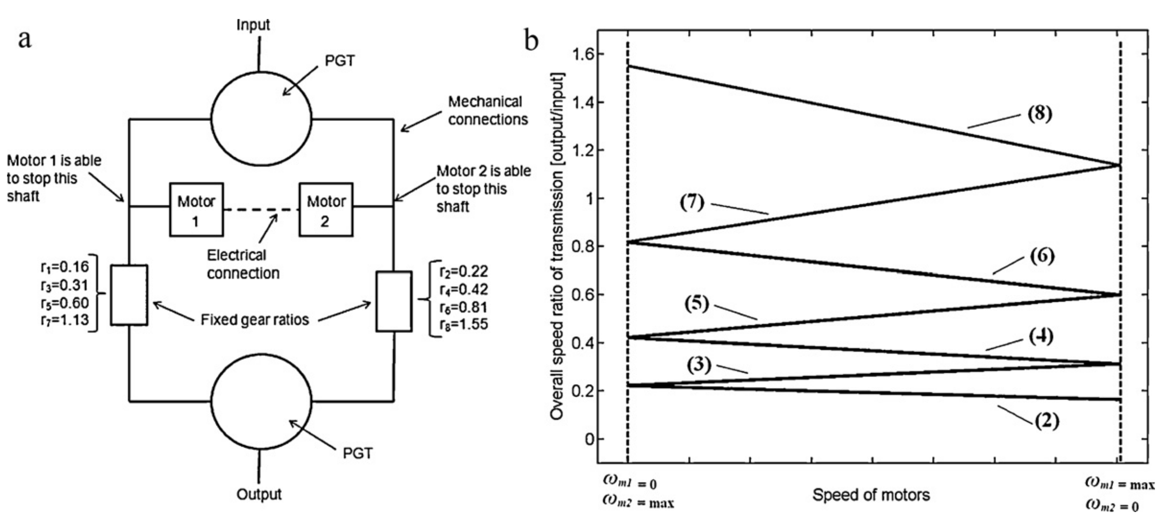

Fig. 4. Operation of the CVT as each motor is stopped: (a) scheme and (b) graph of operation for gear ratio ranges 2–8.

Table 1
Limits of speed ratio ranges of CVT.

Speed ratio range	τ_{min}	τ_{max}
1	0	0.16
2	0.16	0.22
3	0.22	0.31
4	0.31	0.42
5	0.42	0.60
6	0.60	0.81
7	0.81	1.13
8	1.13	1.55

corresponding shaft. Therefore, the fixed gear ratios $r_{1\ldots8}$ shown in Fig. 1 are determined by the combination of the gears being mechanically connected at each branch, by means of the connectors in shafts 1–4.

Let the overall speed ratio of the CVT, τ, be:

$$\tau = \frac{\omega_{out}}{\omega_{in}} \quad (4)$$

The CVT has an overall ratio ranging from 0 to 1.55, divided in eight ranges, termed speed ratio ranges 1–8. When a range is selected, the overall ratio of the transmission varies within two limits, shown in Table 1.

The continuous variation of speed is achieved within each range by means of the electric motors. For the limits of the speed range to be reached, one of the motors, either motor 1 or motor 2, is

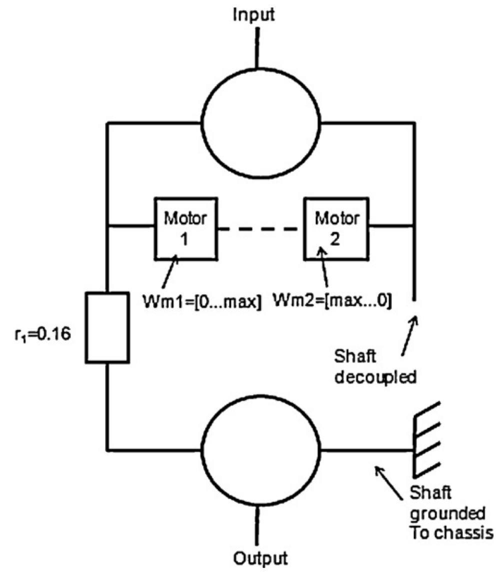

Fig. 5. Operation of the CVT during initial range, with IVT operation.

stopped. The side of the transmission being stopped is alternated to provide continuity (it should be remembered that when one motor is stopped, the other reaches its maximum speed). Both PGTs have the same number of teeth, hence the speed ratio of the

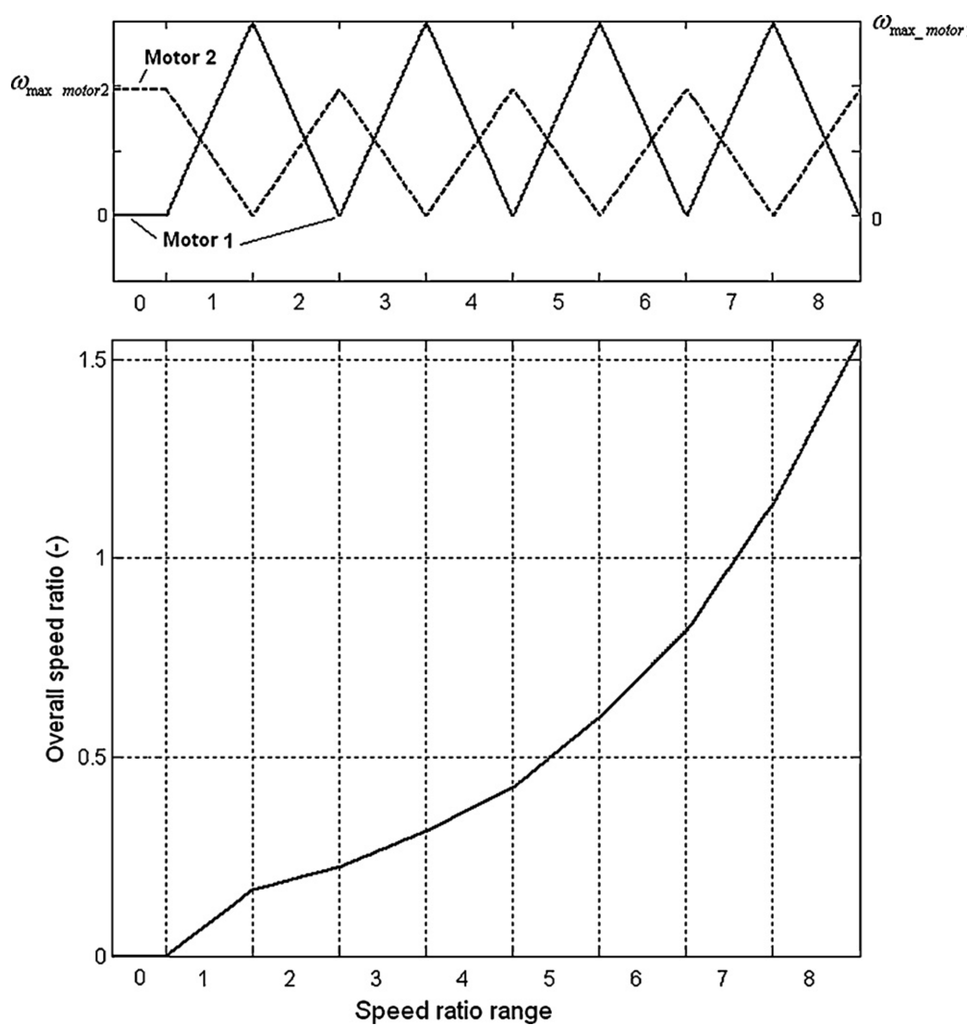

Fig. 6. Example of operation of CVT for the eight ranges (the speed ratio range marked with a '0' corresponds to the mechanism operating as IVT).

whole transmission at each limit matches the gear ratio existing at each fixed step, as shown graphically for speed ranges 2–8 in Fig. 4. The limits where a change in the speed range is done correspond to Eqs. (2) and (3), therefore the performance shown in Fig. 4(b) is always complied for any input speed. When the motor for the corresponding side is stopped, it is viable to move the coupler to make a change of speed because the gears are motionless. In some power split systems the power is divided in two segments: one part goes through a mechanical path with fixed ratio and the rest goes through a variator. In some systems, like the one presented here, one of the ends is stopped. The moment in which this occurs is a singular point, because it is when the fraction of power circulating through the variator crosses zero. It will be further explained is Section 2.2. The CVT subject of this study takes advantage of those singular points to make the speed changes. This is when the singular point transition concept arises: making the change in the gear when there is no power flow in the variator; therefore, in consequence, no movement in a shaft.

The initial speed range has a different behaviour because the mechanism has been designed to operate as an IVT. The infinite variation, where $\tau = 0$, is possible by including a position in the coupler 2 in which the shaft 2 is decoupled from gears C and D. Simultaneously, the shaft 4 of the CVT output is locked to the chassis. Therefore, at the lower limit ($\tau = 0$), the motor 2 is at its maximum speed and the motor 1 spins in solidarity to the load, the vehicle, which is initially standing still. As the vehicle initiates movement, motor 2 reduces its speed and motor 1 increases it. Fig. 5 displays a scheme of this sequence. At the highest limit, when $\tau = 0.16$, motor 2 has stopped completely, which is the initial section for the graph shown in Fig. 4(b).

Fig. 6 displays an example of the complete operation of the CVT.

2.2. Power flow during operation

The objective of the segmentation of the speed ratio range is to reduce the amount of power circulating through the electric path. The presented CVT has been designed to operate with a maximum of 8.7% of power, related to the input, to be transmitted through the motors. This design aims to install low-power electric machines, which enables reductions in terms of weight, space and complexity of the control system that also leads to reductions in cost. When a shaft connected to the motors must be stopped, the corresponding motor operates as generator, taking energy from the corresponding shaft. This power is sent to the other motor, meaning that, simultaneously, the other machine is operating as a motor, accelerating the initial shaft. Both shafts always operate opposite one to the other. In addition, between consecutive speed ratio ranges, the shaft being accelerated is alternated, thus the operation of the motors is also alternated from motor to generator and back again, following a sinusoidal-type graph. The moments in which the sinusoidal crosses zero correspond to the singular points in which changes of the speed ratio levels are conducted. The operation for motor 1 is shown in Fig. 7.

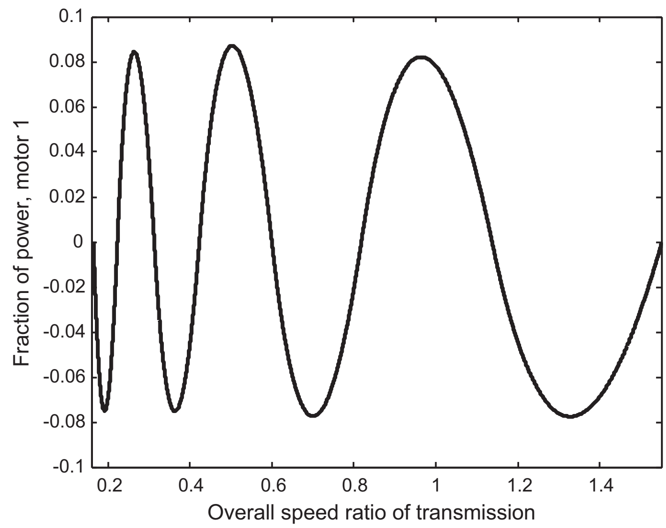

Fig. 7. Power flow in electric motor 1.

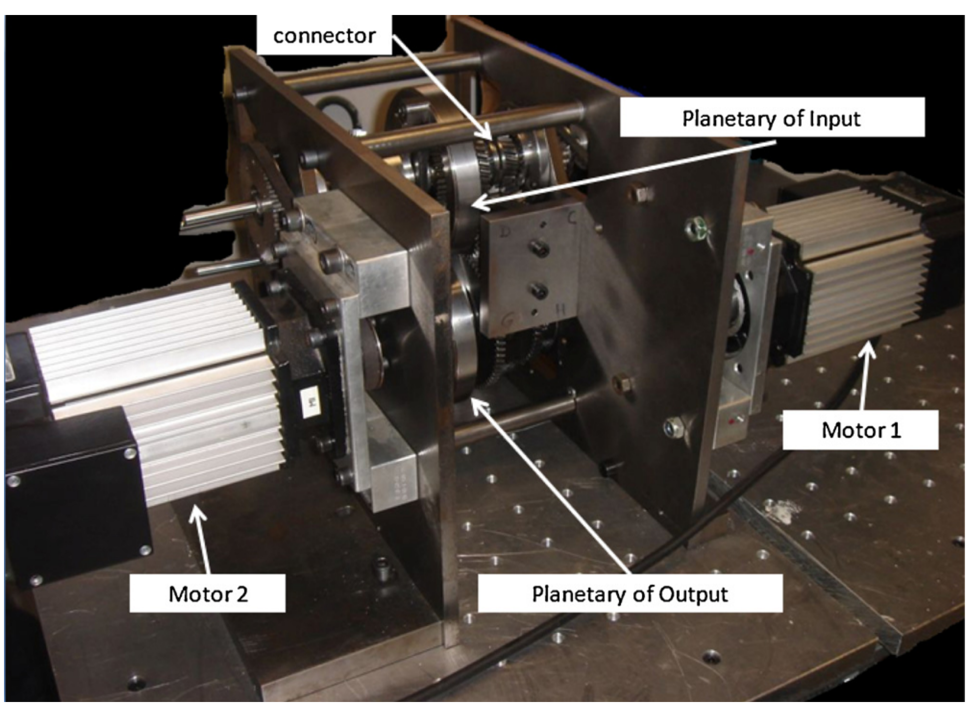

Fig. 8. Photograph of prototype of CVT.

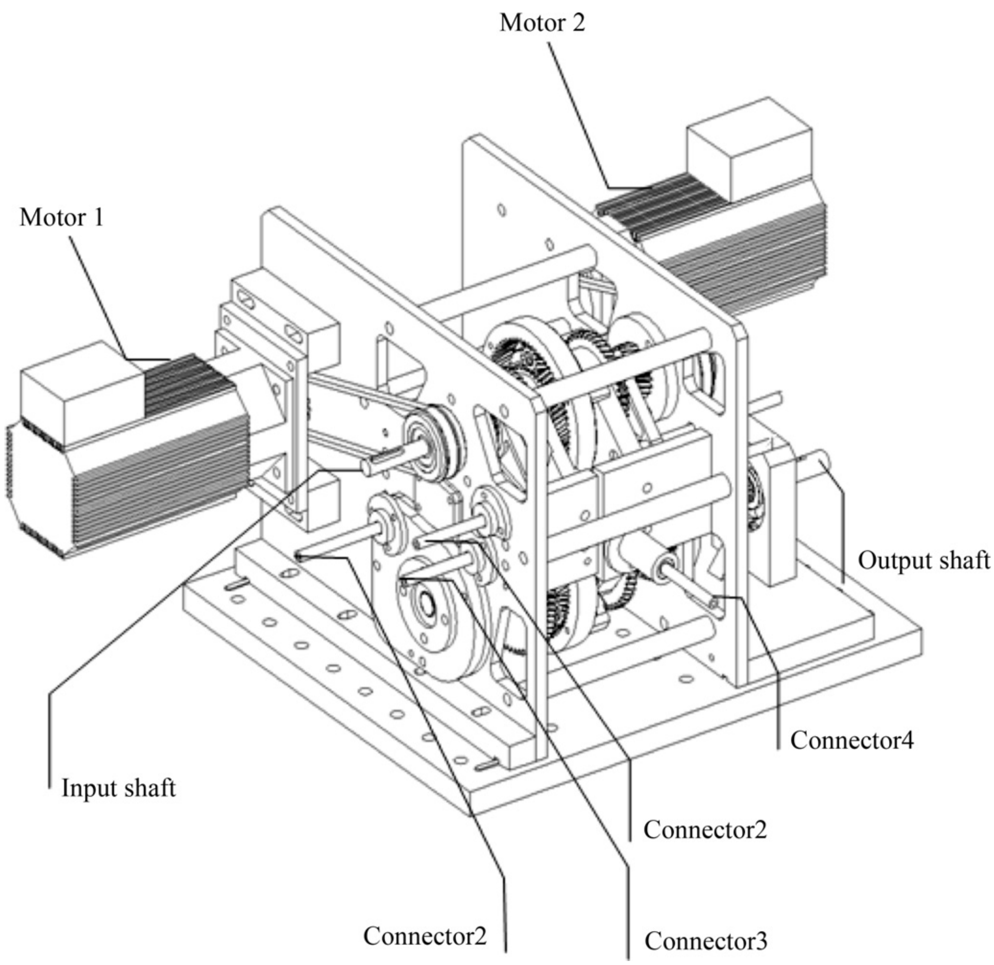

Fig. 9. Main parts of prototype of the CVT.

3. The transmission

A prototype of the transmission, whose photograph is shown in Fig. 8, was built according to the scheme shown in Fig. 3.

The prototype comprises two PGTs, the gear steps, the connectors and two electric motors. Fig. 9 depicts a rear view of the transmission shown in Fig. 8.

The gears, shafts and various parts – some examples are shown in Fig. 10 – were manufactured by Fundació CIM, a partner in the project. 26 gears, 16 shafts and 53 additional parts were produced in-purpose in order to complete the assembly of the proposed CVT.

Two electric motors Mavilor BL114 were installed for control of the speed ratio (motors 1 and 2). A RS-232 bus was used to connect them to a central panel, in which the whole system was controlled using an Infranor driver. The characteristics of the motors are shown in Table 2.

An interface in LABVIEW, shown in Fig. 11, was created for the data acquisition and control. The system was controlled using an Advantech card 1711.

In order to calculate the torque in the Mavilor motors, the authors followed the manufacturer instructions. With the objective of determining the correction factor required for the motors,

Fig. 10. Some gears, shafts and parts of the CVT.

Table 2
Characteristics of motors.

Motor	Stall torque [Nm]	Rated torque [Nm]	Power [kW]	Speed [rpm]	Peak torque [Nm]	Weight [kg]	Dimensions [mm]
BL 114	10.67	8.2	3	0–8000	42.4	7.4	240 × 110 × 110

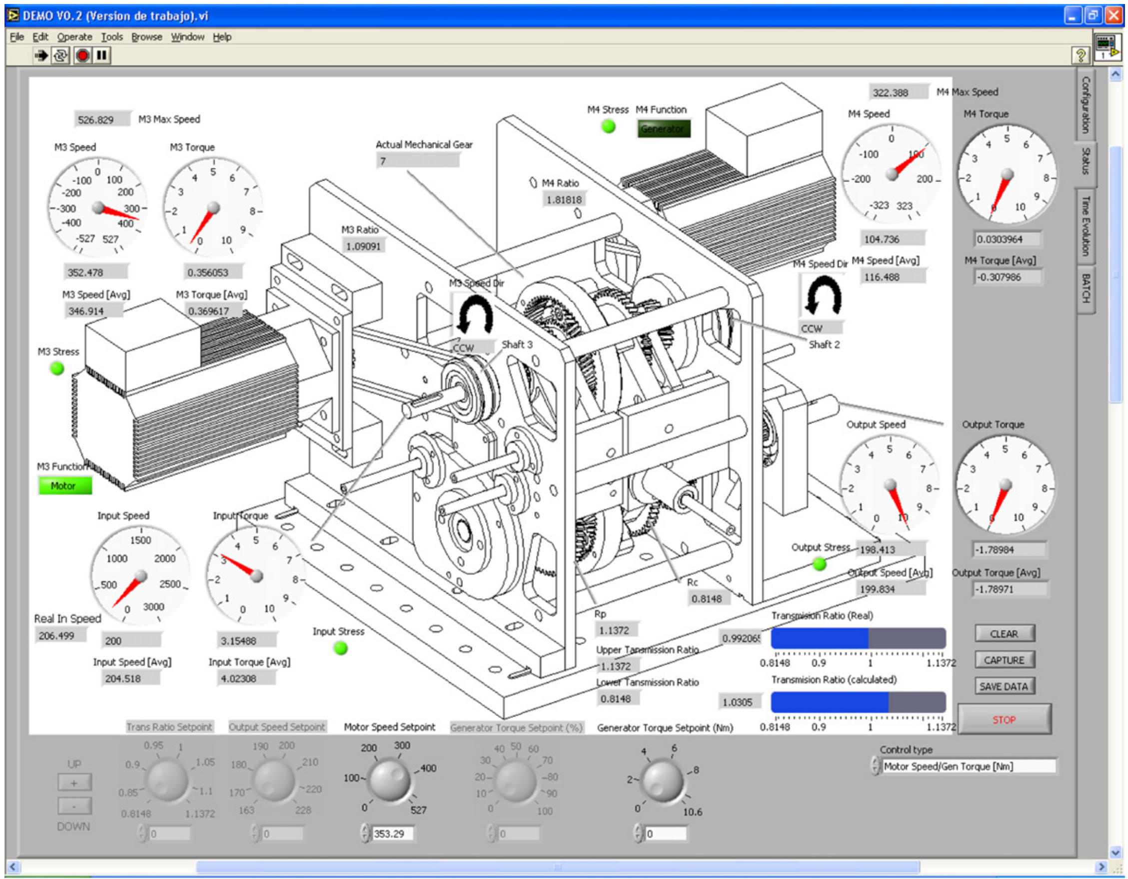

Fig. 11. Labview interface for prototype.

values of torque were verified under static conditions. A dynamometric wrench was used as the reference for these measurements. Fig. 12 presents the set up for the calibration.

Table 3 shows the correction factors with regard to the theoretical value calculated.

The speeds of all electric motors were measured using a laser tachometer. It was verified that the readings of speed where within the tolerance indicated by the manufacturer.

Two AC servo motors Indramat NB-90 were installed to provide power and a resistance load to the system. The complete test bed is shown in Fig. 13.

The torque in the Indramat motors was calculated by the current-based control system, which was calibrated against a load cell. Also, a dynamic system to measure the torque at the motor was built. This system kept the motor suspended in a swing that allowed the case of the stator to rotate. The vertical force associated with the torque generated by the housing was obtained with a lever attached to the swing. This load is the same – due to the law of action and reaction – to that produced by the motor. Finally, the vertical force was measured using a load cell. Fig. 14 shows a photograph of the physical implementation.

The results of the tests are shown in Fig. 15. The load measurement using the control system was considered valid due to its fine adjusts over all the torque working range.

Table 3
Correction factors of mavilor motors.

Concept	Value
Correction factor Mavilor 1257	0.93
Correction factor Mavilor 1258	1.05

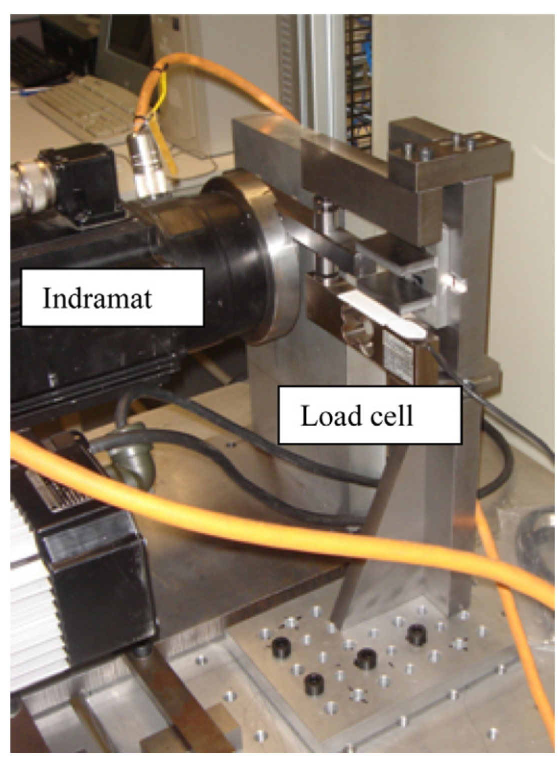

Fig. 12. Measurements of electric load against load cell.

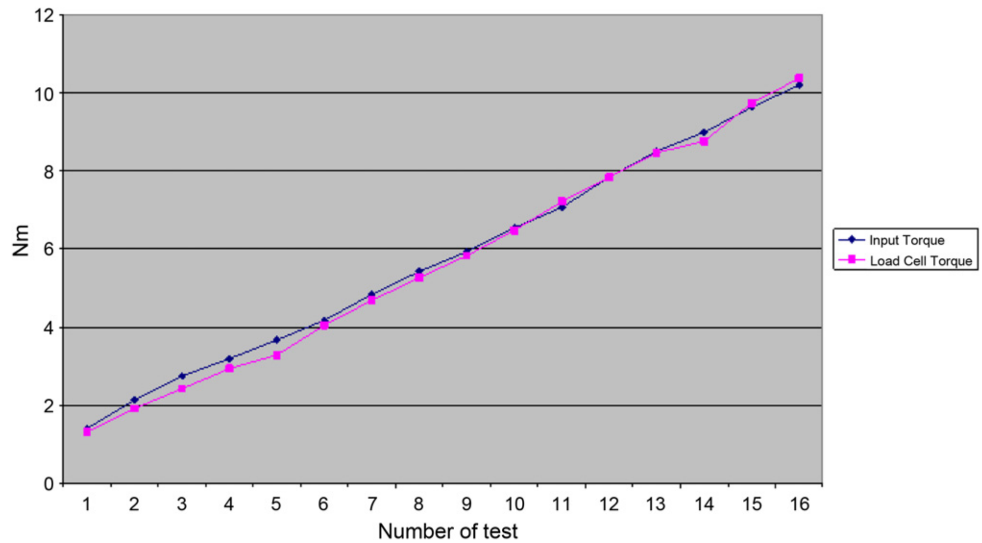

Fig. 13. Results of torque calculated by control system against load cell.

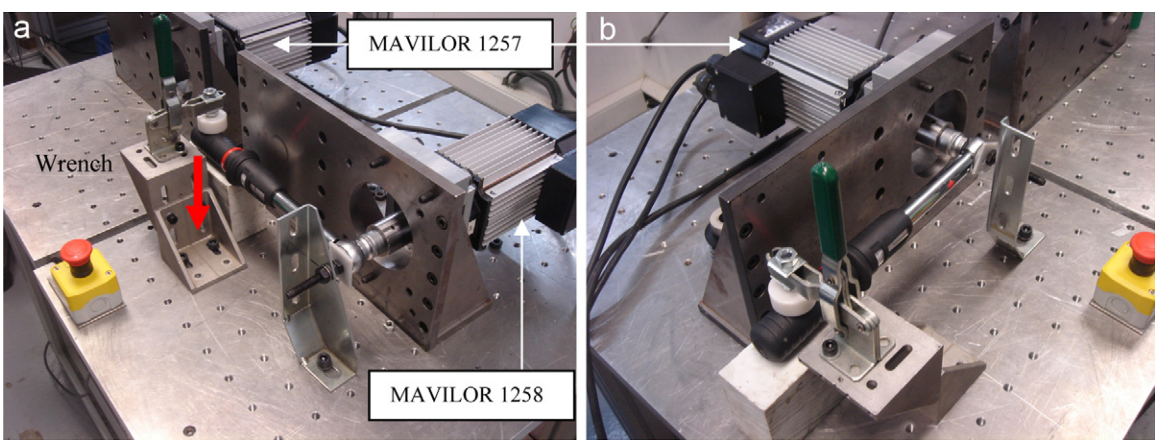

Fig. 14. Verification of torque in mavilor motors.

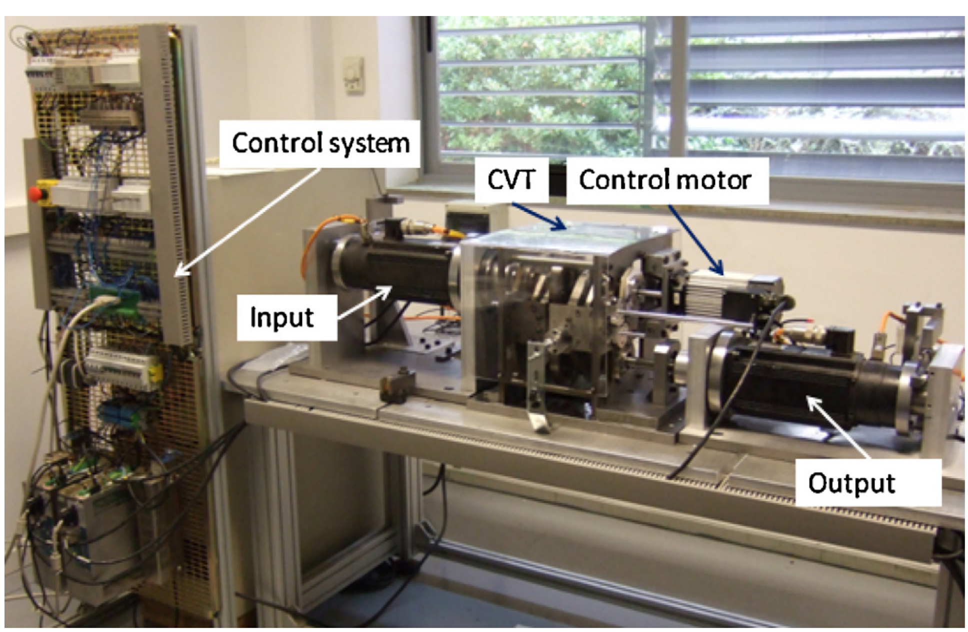

Fig. 15. Complete experimental test bed.

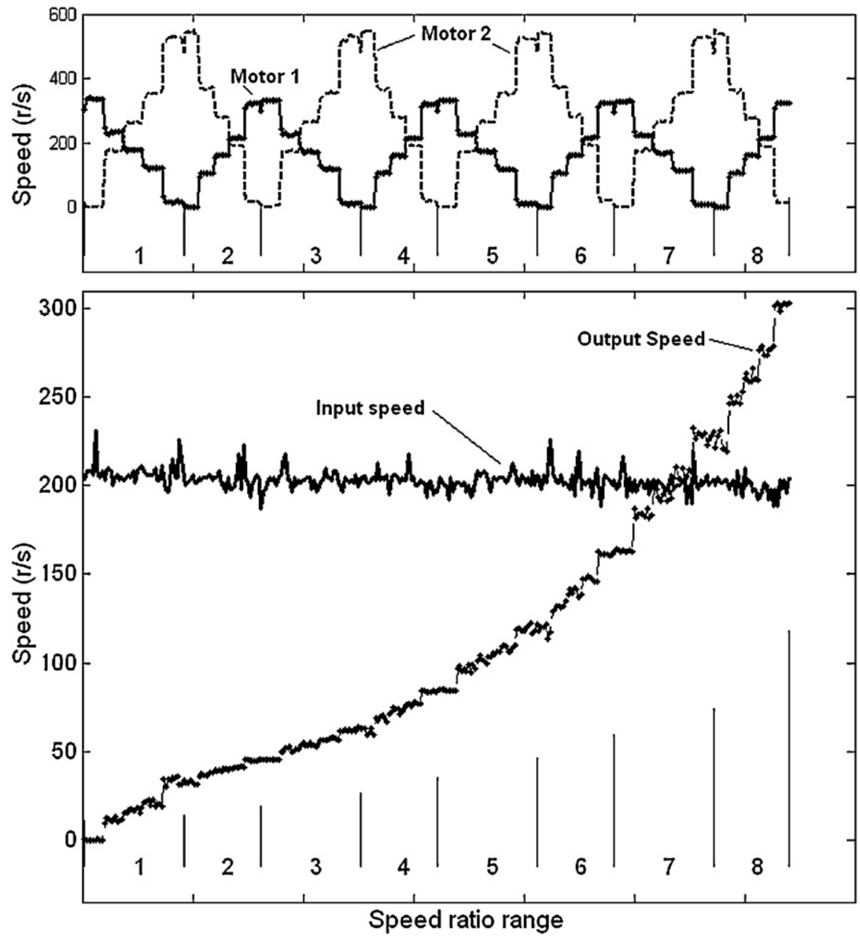

Fig. 16. Test with no load.

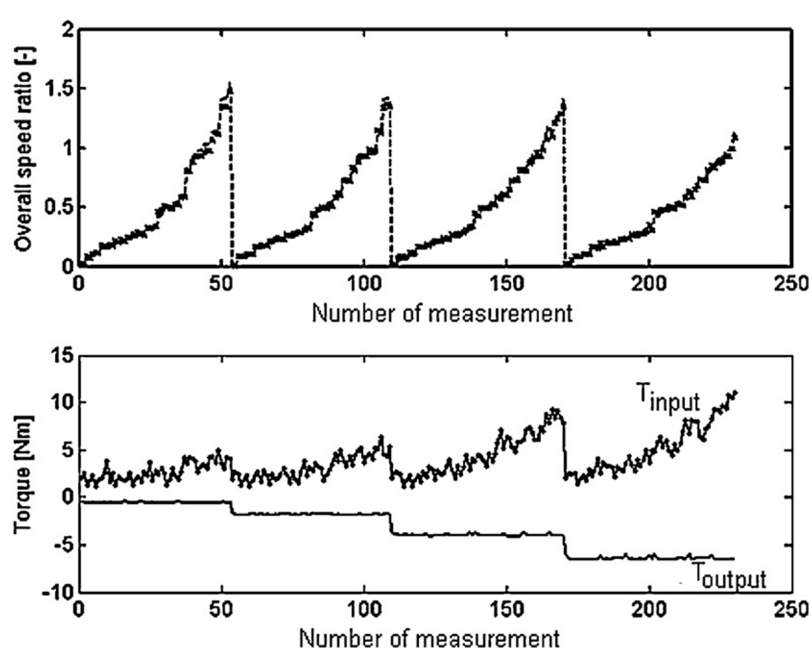

Fig. 17. Tests conducted with prototype of CVT.

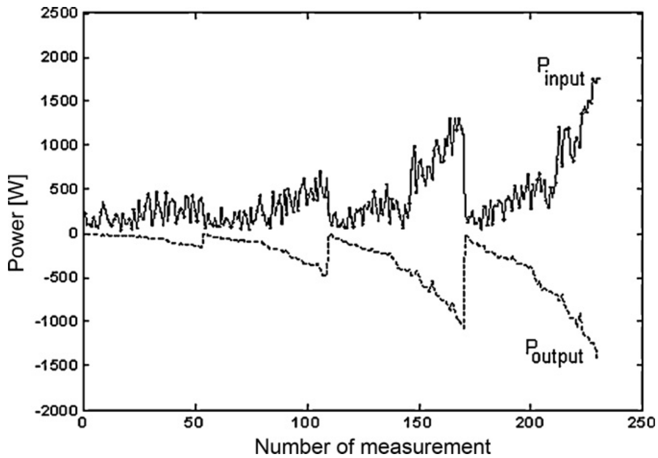

Fig. 18. Power flow circulating in prototype of CVT.

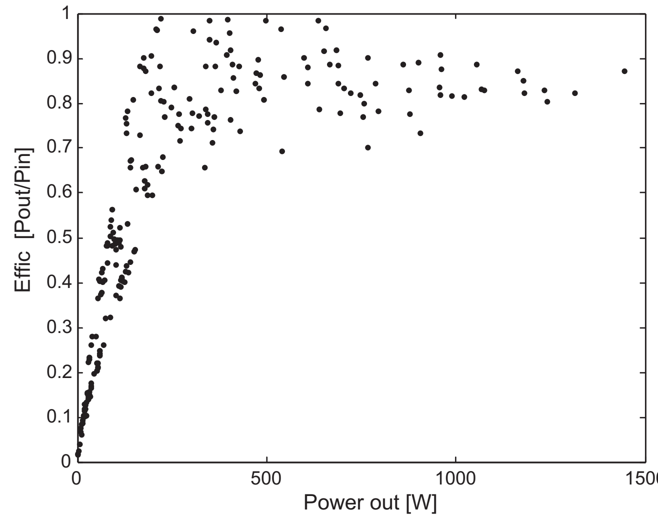

Fig. 20. Efficiency of prototype.

4. Tests and results

Five runs where conducted, one of them with no load applied on the output. Fig. 16 displays the results of the test with no load. In each speed ratio range, the gear transmission was gradually increased around a fifth of the corresponding range. The maximum speed of both motors is clearly seen at each range change.

Fig. 17 presents the results of the other four running tests. In each one, the load force at the output was maintained constant while the overall ratio of the CVT was gradually incremented. During the first run the output load was maintained at 0.5 Nm, with increments of 1.5, 2, and 2.5 for each test to finish in 6.5 Nm. A total of 236 measurements were conducted. The input torque, shown in the bottom graph of Fig. 17, increased due to the gear ratio. It also had an additional increase due to the losses in the CVT.

Multiplication of torque and speed results in the power flow circulating in the CVT, which is shown in Fig. 18. The irregular behaviour in the input power was attributed to some misalignment-related vibrations occurring in the CVT and noise during gathering of data.

A detail of the operation of the motors in the fourth set is shown in Fig. 19. It can be seen that the operation of the motors is alternated for each speed ratio range, operating opposite one to the other.

The ratio of the output and input power determines the efficiency of the CVT, which is displayed in Fig. 20. At low power the efficiency is poor because there is a predominance of constant losses. As the power is increased, contact losses from gears become more dominant, making the efficiency approximate to more standard values. During the performance of the tests, the CVT was inadequately lubricated, thus adversely affecting the efficiency and also a misalignment-related adverse effect in the CVT resulting in a transmission efficiency of 85%. It should be noticed that this efficiency is significantly higher than the current hydrostatic CVTs that have an efficiency level around 70%.

Given that one of the main advantages for the proposed transmission is the low level of power required to circulate through the variable path, an analysis of the power fraction circulating through the electrical path was conducted. Taking into account the effect the power flow level has in the system efficiency; only measurements of power output higher than 800 W were considered. The results shown in Fig. 21 revealed that 80.95% of the measurements lied below a threshold of 8.7% of fraction of power, with a peak of 10.11% of total power circulating through the variator. This indicates that the motors of the transmission were predominantly operating within the expected level according to the design.

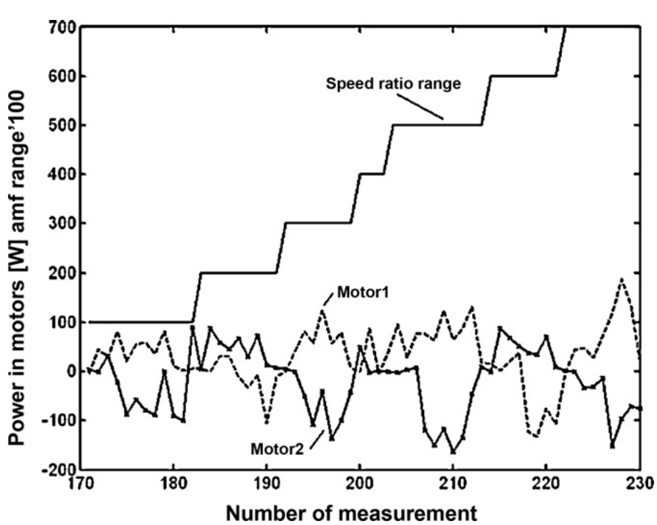

Fig. 19. Motors propelling or functioning as generators during operation of CVT.

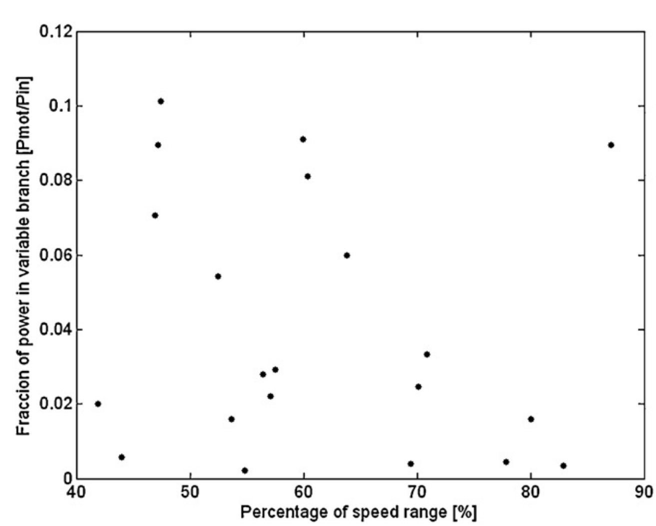

Fig. 21. Fraction of power in variable branch of CVT.

Fig. 22. The CVT transmission designed to fit in a forklift.

5. Discussion

The gathered data demonstrated that indeed it is possible to use the configuration shown in Fig. 3 as indicated in Figs. 4 and 5 to configure a transmission able to operate as CVT. It is a novel type of transmission, thus no previous reference was available; however, it has been seen that the kinematic behaviour of the system operates according to design values. The different output loads tested were valuable to establish that it was possible to control the transmission with different power flows. Although the power ratings in which the CVT was tested were not high enough to establish the limits of the transmission, the results open a vast scenario to continue the validation of the system. Taking this a preliminary stage, the information gathered in the present work enables returning to the design table to explore novelties for the design of the transmission. In particular, a significant step would be to validate that a CVT designed to fit into a standard vehicle power train enclosure is a feasible option to substitute hydraulic CVTs from forklifts (see Fig. 22).

A more refined construction and a better lubrication will further increase the efficiency of the proposed CVT.

6. Conclusions

The prototype of a novel continuously variable transmission was built to validate its principles of operation. An experimental analysis was conducted and the speed and torque of the transmission were measured during operation. The results showed that the transmission was able to operate in the whole range of operation, including operation as an IVT, for different input loads. Also, the results showed that under load conditions the fraction of power being transmitted through the variator remained within the design values (below 8.7% of input power) in 80.95% of the measurements. More research is expected to be carried out, aiming to obtain more refined information of the operation of the CVT and further expand this investigation; however, the results show a promising potential for this novel technology.

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