Giuseppe Pellizzi Prize 2016

[F] PhD Extended Abstract Form *(Please select the Calibri 10 typeface)*

Systematic development and analysis of continuously variable transmissions with inner power split for mobile machinery

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Extended Abstract

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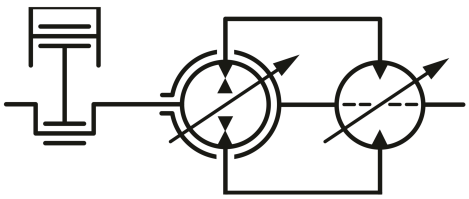
1. Chapter – Introduction

The improvement of the efficiency of mobile machines by using power split continuous variable transmissions (CVT) is usually implemented for machines with a power P>135 kW. The transfer of the known principles to machines with less power is often limited due to a high cost pressure and the available space in these machines. For smaller machines new methods are needed to improve efficiency and comfort and to reduce the lifetime costs.



One of these methods might be the functional integration, which is the principle of inner power split (IPS) transmissions. The power distribution takes place inside of a modified variator, which has the same functionality as a planetary gear. The principle of this kind of variator and the IPS is shown in the figure beside. In contrast to a hydrostatic transmission the IPS allows an additional mechanical power flow directly to the output shaft. By splitting the power inside of the variator the known qualities of power split transmissions can be realised with less transmission components.

In contrast to the known IPS transmissions from the early 1960s the doctoral thesis tries to combine this method by using hydrostatic standard components to benefit from the developments in this area. Therefore an appropriate analysis method is needed which enables a design independent, functional analysis of existing CVT with inner power split and to develop new functional concepts.

2. Chapter – Method development

The comparison of symbolic analysis methods shows that the principle of the torque scheme by *Förster* and *Wolf* is appropriate for the analysis and development of IPS transmissions. Due to the complicate power flows in IPS transmissions the author has improved the method.

By using this method to analyse CVT with inner power split the needed functions of this kind of transmissions are turned out. It is shown that the main difference between the common outer power split and the IPS transmissions is the design of the differential. In a CVT with outer power split the differential is usually a planetary gear set. The main function of the differential is to split or sum several power flows by keeping the torque ratio independent from the speed. Transmissions with IPS integrate the differential function inside the variator (e. g. hydrostatic pump). The needed modification of the variator is the cancellation of the housing fixation. Thereby the variator gets an additional mechanical degree of freedom, so that it gets three degrees of freedom (two mechanical and one hydrostatic) – similar to a planetary gear set (sun, carrier, ring).

3. Chapter – Drive trains of mobile machinery → State of the art

Chapter 3 shows that CVT-transmissions are popular in mobile machines with a power P<100 kW like telehandler, small tractors or wheel loaders. Only machines with this type of transmission achieve a high level of comfort and a perfect use of the installed engine power at every speed. But due to the used principle of CVT (usually full hydrostatic transmission) these machines are limited in the maximum speed and due to a lack of efficiency. Like mentioned before the outer power split transmissions are not applicable for these machines as a result of high cost pressure and the needed space.

4. Chapter – CVT with inner power split (IPS)

With the help of the shown method the needed variator modification could be analysed purposefully. In all cases the housing fixation of the variator must be solved for an additional power flow. This power flow comes along with an additional shaft or a rotational degree of freedom. As mentioned before this modified variator has three paths for the power flow, which is similar to a planetary gear set.

To find the best variator principle for small mobile machinery the 4th chapter makes a comparison of variator principles in transmissions with IPS. Beside the hydrostatic variator (pump and motor) the specific characteristics and the needed design modifications of hydrodynamic, electrical and mechanical variators are described.

In the hydrodynamic variator the housing fixation of the guided wheel is eliminated. Due to this additional degree of freedom the possible torque increase at vehicle start can be enlarged. Nevertheless it is not possible to use a hydrodynamic variator for a regular drive train transmission.

The electrical variator consists of two machines - generator and motor. To create a transmission with IPS the housing fixation of the stator of one of the both electrical machines is solved (= differential) and connected to the rotor of the second machine. Because of the limited torque and power density the variator doesn't fit for mobile machinery.

The modification of a mechanical variator (e. g. friction wheel drive) hasn't been done before. These kinds of variators have a very good efficiency but a low torque capacity so that they aren't in the focus of this work for mobile machinery. Nevertheless the potential is huge for commercial vehicles so that this idea has been patented during the PhD studies.

Due to the potential of today's hydrostatic units the doctoral thesis focused on the modification of the existing hydrostatic drivetrain in small mobile machines.

5. Chapter – Synthesis of transmission with IPS

With the developed method the potential of all theoretical drive train concepts with IPS is analysed. The focus vehicle for the potential evaluation is an agricultural used telehandler. This vehicle has today a hydrostatic drivetrain with a variable swash plate pump and two bent axis units. Following the suggestion of *Renius* a goal for the full load efficiency of the telehandler transmission is defined.

Beside the three main groups of power split concepts further IPS concepts have been invented. A dimensioning of each hydrostatic IPS concept is shown for the focus vehicle. For the efficiency evaluation the analysis of the power flow through the hydrostatic variator-differential is needed. Following the efficiency calculation of planetary gear set an approach for a hydrostatic variator-differential has been developed and implemented in the efficiency simulation of the transmission concepts. With this analysis transmission concepts could be developed which show a significant improvement of the efficiency – especially at high speeds (approx. 20 %).

6. Chapter – Design of hydrostatic transmission with IPS

For a cost optimised transmission with IPS the usage of standard components is mandatory. Due to this goal the author developed a modular design method for transmissions IPS. This reduces the effort of the needed adaption of standard transmission tremendously. For instance the modification of the focus vehicle with a full hydrostatic drivetrain just has to concentrate on the adaption of the hydrostatic pump. The hydrostatic motor can remain the same.

Like shown in chapter 4 a standard axial piston pump in swash plate design is modified to integrate the function of the differential. Therefore the swash plate of the pump needs to rotate with one shaft in addition to the piston barrel, which is connected to a second shaft. It is intended that these two shafts can rotate independently from each other. In that case this kind of variator-differential is a combination of a wobble plate (fixed piston barrel) and a swash plate pump (fixed swash plate). To keep as many components of the standard swash plate pump several technical innovations were needed. Altogether this resulted in seven further patents. These patents describe for example the adjustment of the wobble plate without any 'wobble effects'. This has been necessary for a speed independent control of the variator-differential and a reduced control pressure.

At the end of chapter 6 an additional design study shows a comparison of a standard swash plate pump and the developed variator-differential. Both variators have a similar volume and weight, so that an implementation in the standard drive train is possible by an exchange of the standard pump with the variator-differential.

7. Chapter – Functional proof of a hydrostatic variator-differential

The proof of concept is described in chapter 7. Therefore a test bench was developed to proof the differential functions of the functional model. Two electrical motors are in each case connected to the input and the output shaft of the variator-differential. With a speed control of both machines any needed speed combination of input and output speed could be set. For instance it has been possible to proof the adjustment concept by operation of the functional model in wobble-plate mode (fixed piston barrel; rotating swash/wobble plate). By defining several speed combinations the hydrostatic power flow, which is dependent on the relative speed, was proofed. Furthermore it could be shown that the hydrostatic variator-differential has a defined torque-pressure-relation – independent from the actual speed. In contrast to a planetary gear set this relationship can be changed by the adjustment of the swivel angle, which is essential for the direct usage of the variator-differential as a start-up element of the vehicle. Thereby the condition of the modular design concept of CVT with IPS is fulfilled.

Final remarks concerning the competition benchmarks and strength points

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- The doctoral thesis shows an approach to make an economical efficiency and comfort improvement of mobile machines with low power.
- The developed approach combines a functional integration with a modular concept to ensure an easy integration in existing drivetrains for mobile machines. Thereby 8 patents could be applied which have also an impact on other fields of application.
- The concept allows an improvement of efficiency up to 20 % with the space and expense of a common drivetrain.