

Concept of Mechanically Powered Gyrobus

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ABSTRACT: The new gyrodrive concept is an innovation of the mechanical gyrobus transmission by Hampl & Vitek 2006. The legitimate aim of substituting urban buses with zero emission vehicles is actually very difficult to achieve. First of all, no existing non-rail vehicle for urban mass transport can compete with urban buses in terms of cost. Even trolleybuses on the busiest lines are less economically efficient. In addition, they lack the flexibility of buses. Electrobuses with their heavy and slow to charge accumulators are almost as expensive as fuel-cell buses whose specific problem is the refueling with compressed or liquefied hydrogen. A gyrodrive does not face such problems and it is also reasonably safe. But even a modern electric system for power transmission from the flywheel to the driving axle is neither light nor cheap. A mechanical solution with CVT (Continuously Variable Transmission) can be more advantageous. Such a system has been used for recuperation of braking energy. The mechanical system described in this article uses an IVT system (Infinitely Variable Transmission) for the vehicle drive. If that system is used for flywheel charging at the terminal, it will be connected as CVT (by using an external three-phase 50 Hz electromotor). The higher-than-average requirement for transmitted power should be met by the suggested special CVT solution with rigid friction members. Thanks to its planetary configuration it has acceptable dimensions and mass. The slip minimization and the fact that the pressure forces do not load the bearings should ensure a good efficiency.

KEY WORDS: Gyobus, mechanical power transmission, CVT, IVT, planetary differential.

1 INTRODUCTION AND MOTIVATION

1.1 History

The first electrically driven road vehicles independent of a trolley wire were made in Europe and in the USA as early as the late 19th century. These included mainly vehicles with electrochemical current sources. Such sources have prevailed at electrocars and electrobuses until now. But despite a long and concentrated research on electrochemical sources, the relationship between their price and lifetime is still almost unacceptable for use as vehicle drive. They also have other undesirable attributes: in the case of fuel cells, used now in many experimental vehicles, in particular electrobuses, the main problems concern the distribution and refuelling of expensive hydrogen, whether in compressed or liquefied form. Problematic attributes of electrochemical accumulators are as follows: relatively slow charging (particularly towards the end), insufficient reliability, energy capacity reduction during their lifetime, power and exploitable energy capacity linked to temperature and destructive influence of a deep discharging on the battery lifetime.

Such disadvantages are not associated with the kinetic energy accumulation. However, flywheels have another serious drawback: fast self-discharging, which makes their use in electrocars almost impossible. But this is not relevant for urban mass transportation vehicles. They have regular and short routes with breaks at terminals where there is enough time for charging the flywheel fully (but not for full charging any electrochemical accumulator). This is how the idea of gyrobus came about.

The first regular gyrobus transport started in Switzerland in October 1953, on a 4.5 km-route between Yverdon-les-Bains and Grandson. The most extensive use of those gyrobuses was in Leopoldville (today's Kinshasa in the Democratic Republic Congo, Africa) where they operated until 1969.

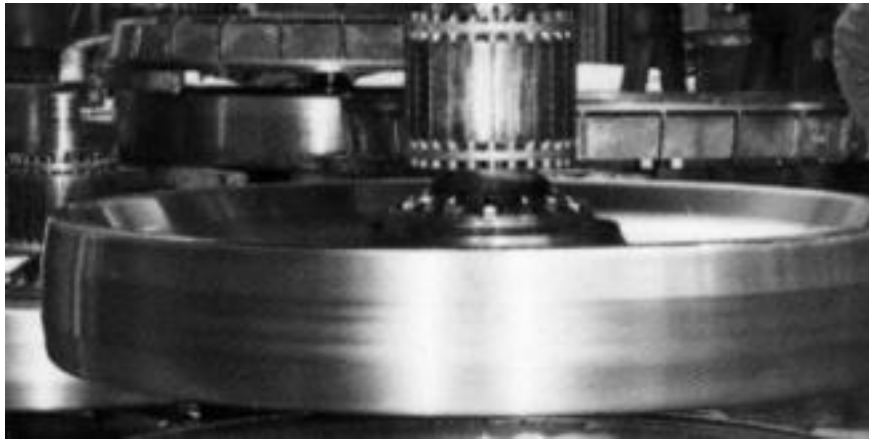


Figure 1: Rotor of the asynchronous motor-generator and steel flywheel of the FMO gyrobus

Their gyrobus drive was developed by the Swiss company Oerlikon. Its flywheel of compact steel had a vertical rotation axis and an external diameter of 1.6 m . Its mass was 1500 kg . It was coaxially connected to an asynchronous motor-generator. During the “refuelling” (about 4 minutes, 150 kW) the motor-generator was powered from the common three-phase 50 Hz network by using bar collectors on the vehicle roof. The maximum motor speed was 2900 rpm and its minimum operation speed was 2300 rpm . Therefore 63 % of the accumulated energy was non-utilizable. When the vehicle was running this asynchronous generator supplied the current to the three-phase asynchronous traction motor. The main control was performed in steps by switching over of the poles.

1.2 Present solutions

Current technology allows a step-less and entirely smooth control of flywheel propulsion over a wide running speed range, and also minimizes the consequences of an unlikely material destruction. That is to say that in the area of inertial energy accumulation a lot of theoretical and experimental work has been performed with positive results, particularly in the USA. The new “super-flywheels” make use of light materials such as glass type E, aramid or carbon. In the form of a filament they are extremely strong. A wound flywheel can also accumulate more energy due to the permitted low safety coefficient (a ruptured filament will be disarmed by the flywheel box without endangering passengers or pedestrians).

In order to eliminate ventilation losses such a flywheel runs in the vacuum and it is directly connected to a synchronous motor-generator whose rotor has permanent magnets, e.g. made of Fe-B-Nb alloy (electromagnets would need cooling which is difficult in the vacuum).

One of the first similar solutions was an inertial accumulator developed by NASA for supplying electric energy to satellites when they pass through the Earth's shadow, where the

photocells do not work (an electrochemical accumulator would work there for only a few months). Chrysler used 15 of these sources for the powering of an experimental electrocar.

A more significant in this context were additional flywheel units for urban buses or trolleybuses used together with main energy sources to cover the peaks in consumption and for regenerative braking (possibly also for a short independent drive). Such units were installed by the Magnet Motor GmbH in two urban buses in Munich in 1988, and in twelve trolleybuses in Basle in 1992. Their carbon filament flywheels had a maximum speed of *12,000 rpm*. Their relatively high extra mass was also unfavorable for use in road vehicles.

The Kinetic Energy Recovery Systems (KERS) with a mechanical transmission of power by using CVT are lighter. For example the company Hybrid Automotive Limited has developed the Flywheel Hybrid System for Premium Vehicles (FHSPV for Jaguar XF prototype). Another their set designed to meet the FIA regulations for the Formula One is shown in Fig. 2. Its accumulated energy is *400 kJ (60,000 rpm)*, its additional power *60 kW* (limited by its toroidal CVT). Its total weight is *25 kg* and volume *13 litres*.



Figure2: Flywheel unit combined with the TOROTRAK CVT as auxiliary drive for F1 racers

Concerning rail vehicles, the increased price due to the installed flywheel unit is not dramatic and the mass increase is hardly relevant. Therefore, an auxiliary flywheel unit made by the rosseta Technik GmbH was installed into the LIREX articulated train produced by Alstom LHB. Its carbon fibre flywheel had a net mass of *160 kg*, a maximum speed of *25,000 rpm*, a maximum accumulated energy of *6 kWh* and a maximum output of *350 kW*. Its specific energy of *135 kJ/kg* was comparable to that of CD-Ni accumulators. (The new lithium batteries, e.g. LiFePO_4 , have a higher specific energy but such a flywheel can outperform them in terms of power. Its lifetime, measured in cycles, is more than 1,000 times longer.)

The flywheel together with the rotor of the motor-generator runs in its box on ball-bearings lightened by permanent magnets. The bearing losses do not exceed *200 W* but the losses in the motor-generator during its idle run were *3.5 kW* (causing fast self-discharging). Therefore, the producer recommended its use only for applications where charging or discharging lasts only about ten minutes.

Our intention is to significantly extend that time by a radical restriction of self-discharging so that the flywheel could be used as the only energy source for the gyrobus drive. Furthermore, we want to increase the total efficiency and reduce the mass of the entire gyrobus propulsion unit to the level of the standard bus engine-gearbox assembly. We also aspire to cut the price of the unit.

2 PRINCIPLE OF THE NEW GYROBUS DRIVE

We expect to use a nearly identical design for the composite flywheel as noted above but we will replace the electric power transmission from the flywheel to driving wheels with a fully mechanical one. An Infinitely Variable Transmission (IVT) will be used for this purpose. That should result in a substantially decreased self-discharging, increased total efficiency and a smaller mass. The price is also expected to decrease.

A disadvantage of the mechanical transmission is the leeway loss due the dislocation of drive components in the vehicle. Concerning the placement of the flywheel, a parallel orientation of its rotation axis to the vehicle transverse axis would be favorable because if the flywheel rotation is reverse to the vehicle wheels rotation the gyroscopic moment counteracts the tilting torque of the centrifugal force during the vehicle turning.

The rpm has linear influence on the gyroscopic moment but quadratic influence on the accumulated energy. So, if a high speed flywheel and a low speed one have the same accumulated energy, the high speed flywheel will have a lower gyroscopic moment. Therefore its axis orientation is not very important (for example in case of our gyrobus the maximal lateral force on the axles generated by both flywheels during a very rapid turning of the vehicle can reach approx. 1 kN).

Because of the low-floor concept the drafted gyrobus has individual drive for each rear wheel. So, two flywheels are used. They are placed together with the IVT systems under fours of passenger seats (2 + 2, dos à dos on the elevated floor). Similarly, under the next four seats the driving wheels are situated, see figure 3:

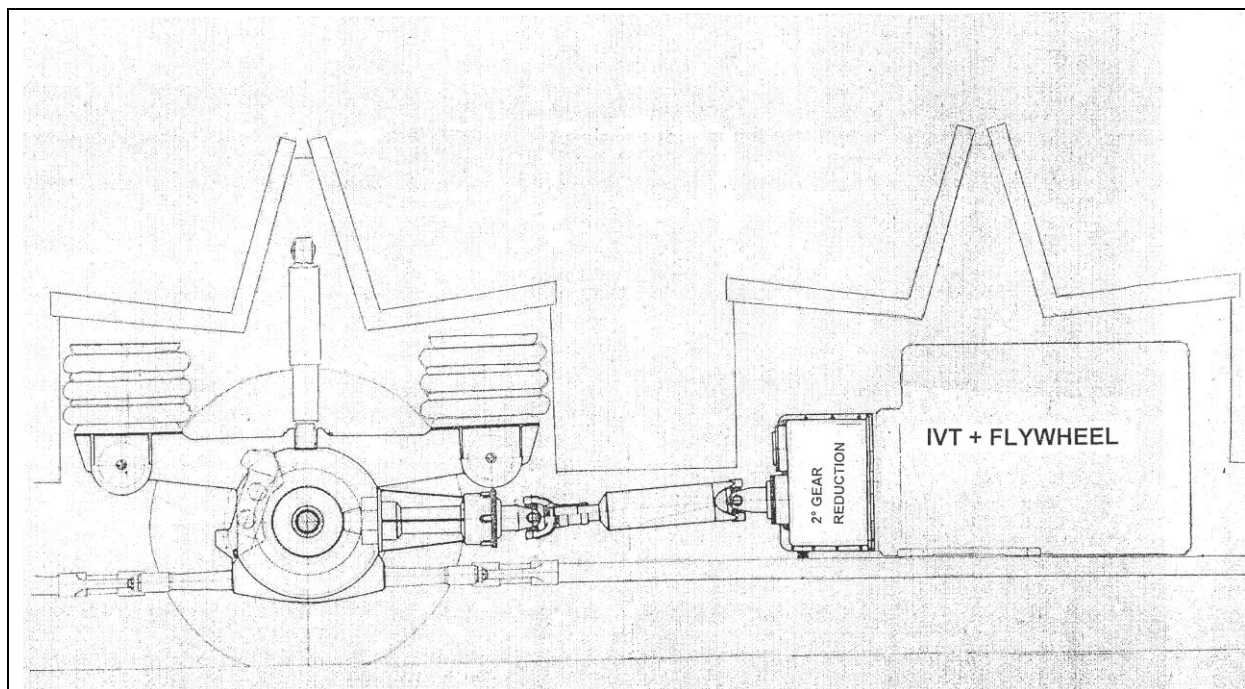


Figure 3: Scheme of individual drive for each of both rear wheels of the low floor gyrobus

The flywheel rotational axes are parallel with the longitudinal axis of the vehicle. The special drive of the rear wheel is illustrated in figure 4:

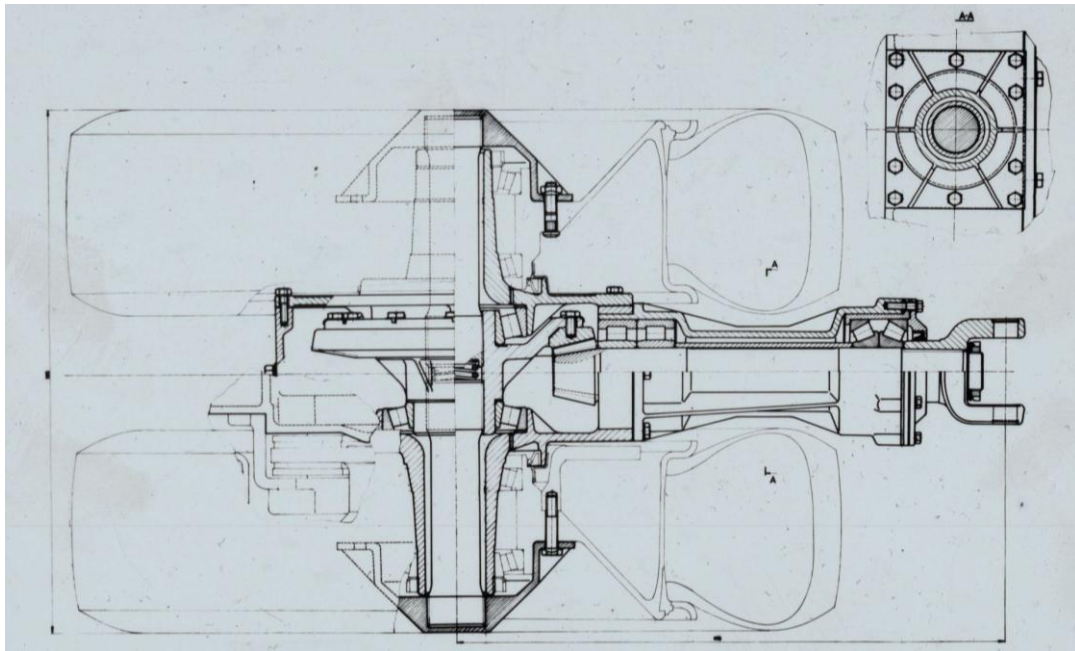


Figure 4: Special drive of the rear wheel (inner tyres are mountable from the vehicle interior).

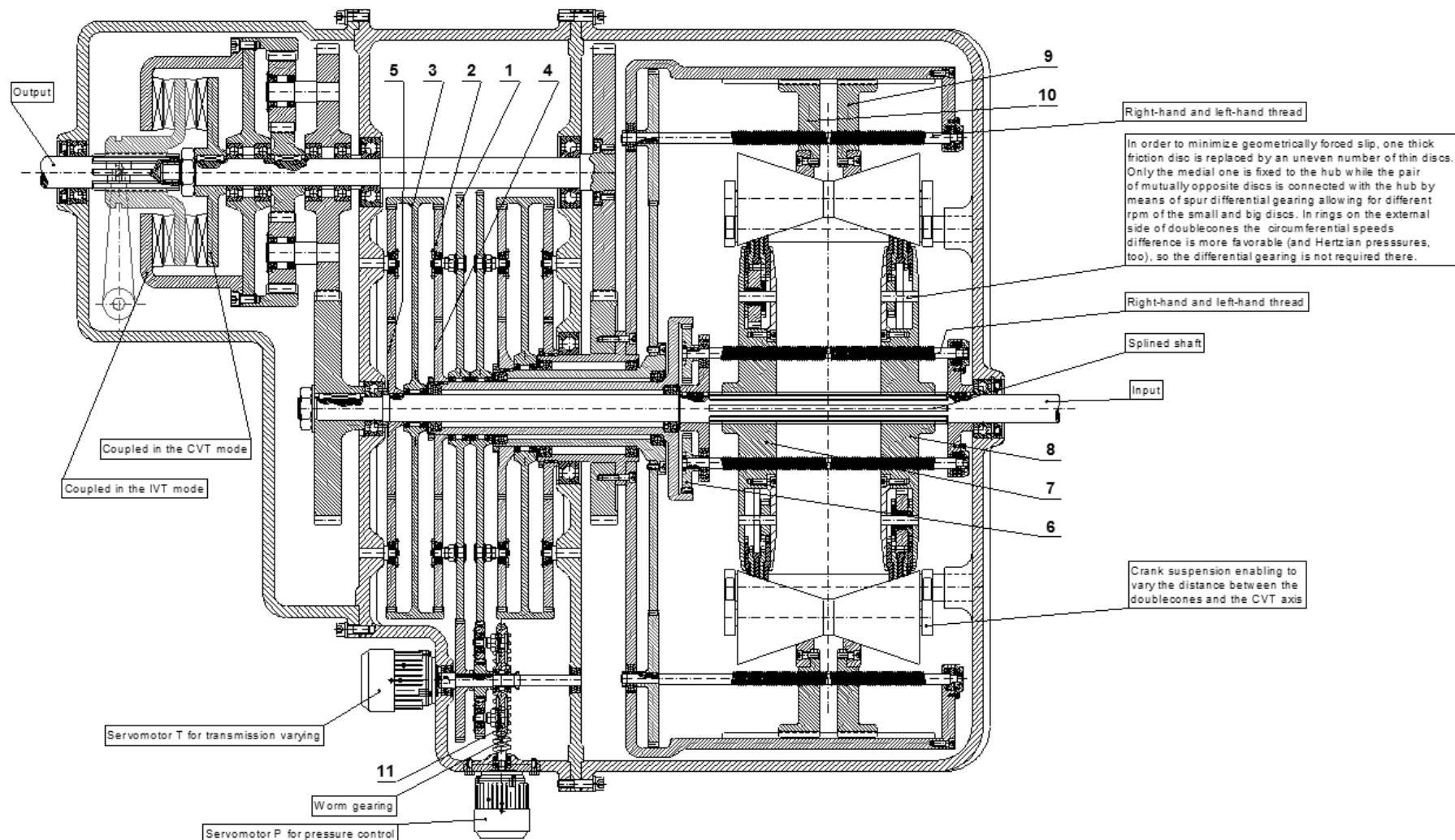
In order to minimize ventilation losses there will be the vacuum in the flywheel box and rarefied hydrogen in the IVT box. Compared to air, hydrogen has half the kinematic viscosity, 14 times lower specific mass and it better conducts away the heat produced. The vacuum in the flywheel box must be renewed by an on-board exhauster (at terminals only). The hydrogen infiltrates into the flywheel box from the IVT box along the shaft sealing, and into the IVT box from the bearing inter-space where it is replenished from a small container. The filling pressure must be slightly higher than the atmospheric one so that no explosive mixture can result due to air penetrating from the outside.

3 THE NEW CVT AND ITS OPERATION AS IVT

Currently produced CVTs are installed into cars with a considerable output surplus available so that the CVTs mostly transmit only a small part of the presented maximum torque. Also, the number of service hours is far lower for cars than for urban buses. Therefore, such CVTs would not work well for a gyrobus. However, this is not the only reason - they are not high-speed enough either.

Therefore, our draft considers an IVT that is based on the planetary CVT presented in figure 5 (next page). This planetary CVT outdoes existing CVTs with rigid friction members by:

- small dimensions, mass and moment of inertia in relation to the transmitted torque;
- allowing transmission of big tangential forces due to a high number of contact facets between the friction elements (48 co-operating facets between disks and double-cones);
- a total absence of the “spin” slip type;
- using the mechanical transmission ratio control (energy savings due to the absence of a hydraulic pump);



Functioning of speed change mechanism: When servomotor T through an angle turns the toothed wheel 1, the satellite 2 spins inside the ring gear 3 whereby the sun gear 4 is slewed towards the adjacent sun gear 5. That gear 5 is connected with the input shaft which is situated inside of the hollow shaft in the most internal position and connected with the sun gear 4. The mutual slewing of these shafts leads to the slewing of the gear 6 connected with the screw with right-hand and left-hand thread. It results in the change of distance between pulleys 7 and 8. The distance between rings 9 and 10 is being changed analogously.

Functioning of pressure control mechanism: While with the speed change process the pulleys are shifted against the rings, with the pressure change the pulley and the ring move in the identical direction (not counter direction). Such a motion is forced into the system by the differential whose carrier 11 is driven by servomotor P through a worm gear.

Figure 5: Hypothetic scheme of mechanically controlled IVT (both pressure and gear ratio are actuated)

- a small slip forced by geometry (“creep” type) due to the differential linkage of the parallel friction elements as they are illustrated in figure 6;
- axial pressure forces (figure 7) avoiding the bearings; it ensures, together with the small slip, good efficiency;
- a low value of Hertzian pressure between (see figure 8); the maximum Hertzian pressure (1.35 GPa - TOROTRAK admits 4 GPa) is achieved in sporadic cases only: when a big output at the minimum operating r.p.m. is required during the maximum or minimum transmission ratio; that ensures long life of friction elements without requiring any extremely high quality material for them.

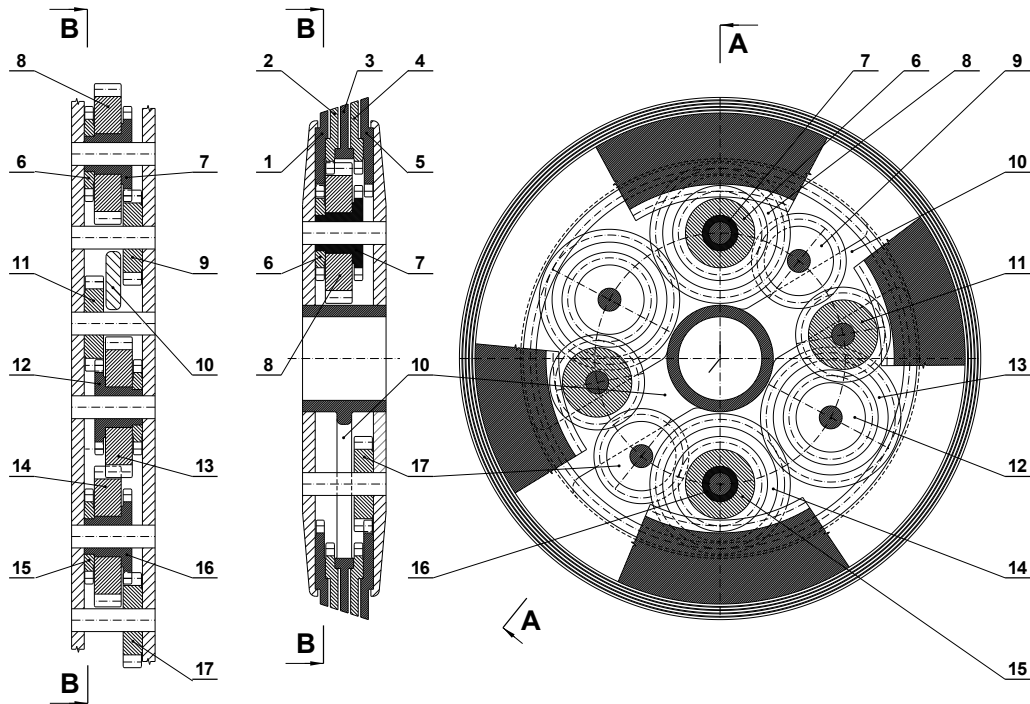


Figure 6: The conic pulley composed of discs forced to rotate with uneven rpm when rolling.

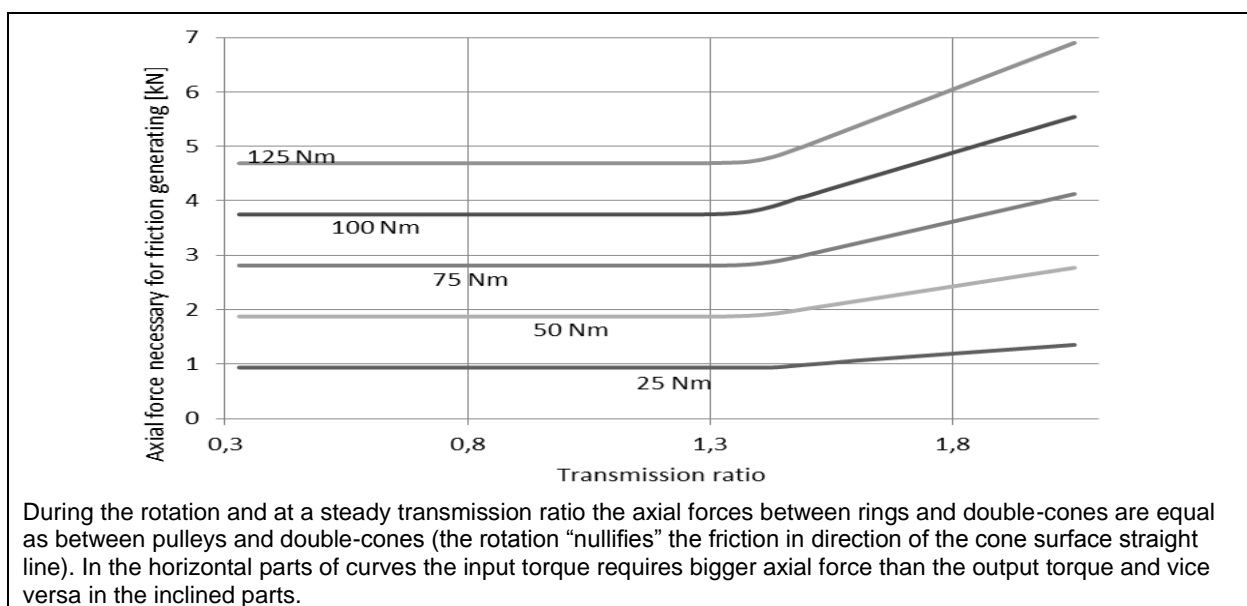


Figure 7: Axial forces between friction members depending on torque and transmission ratio.

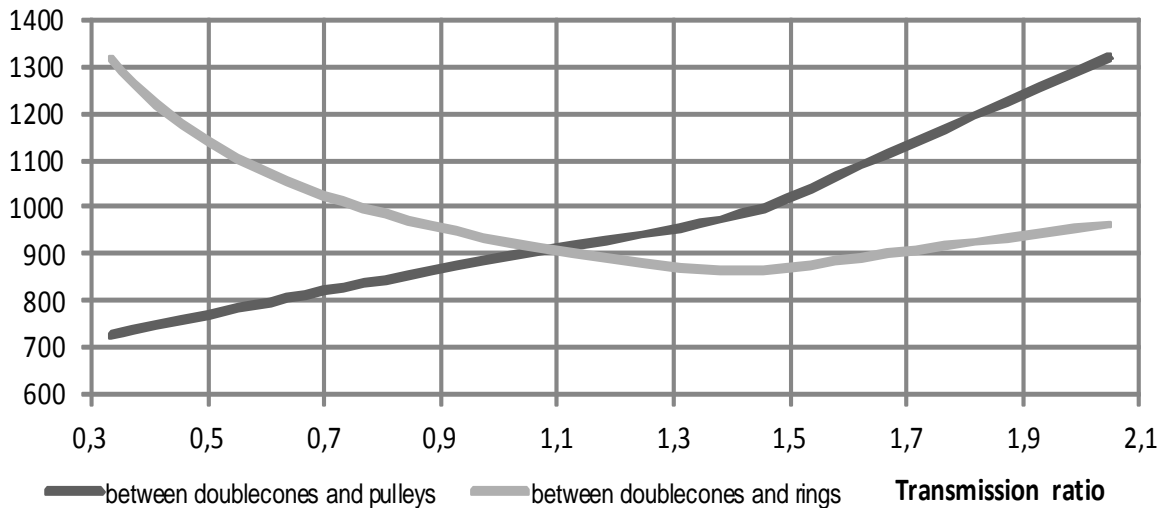


Figure 8: Hertzian pressures [MPa] at maximum input torque (125 Nm).

The mechanical control of the transmission ratio change is implemented by a mutually opposite shift of friction disks (and rings) by means of screws with right-hand and left-hand threads (Fig. 5). This ensures a permanent perpendicularity of pulleys and rings to the rotational axis during their shift. The mechanism concerned is driven by an energy saving electric servomotor. Mechanical actuation is also used for the mutual thrust of friction members by using a worm gearing for the second servomotor. This type of self-locking gear makes it possible to nullify its incoming power when the thrust maintains a steady value.

3.1 Modes of transmission system

It is not possible to control the speed of a gyrobus (unlike bus and trolleybus) by varying the power source rpm. There is only one method for doing this: continuous varying of the transmission ratio. The variability range must be considerable, also owing to counteractive changes (when the vehicle speed increases the flywheel rpm goes down and vice versa).

For our purposes current mechanical CVTs have insufficient transmission ratio. We can extend the ratio if the CVT collaborates with a differential, changing the transmission into an IVT (Infinitely Variable Transmission). Then the vehicle can move without using a clutch and it will be possible to decelerate and stop without using friction brakes. In the IVT mode the flywheel will be connected to the differential in two ways: both directly (e.g. with the planet carrier) and by means of CVT (e.g. with the sun wheel). Then three different modes can be identified at the output (ring gear):

- Pseudo-locking mode. Although the connection of the flywheel with the vehicle driving wheels is not interrupted the vehicle is stopped as if the parking brake had been used. In this mode the sun wheel (driven by the CVT) turns round faster than the planet carrier in order for satellites to roll in the stopped ring gear. Such a situation occurs when the CVT transmission ratio is nearly the quickest one.
- Reverse. The absolutely quickest CVT transmission ratio is used (the return motion does not require any gear shifting).
- Driving forwards. When the CVT transmission ratio starts getting slower (from the pseudo-locking mode) the sun wheel rpm decreases; however, without any rpm change of the planet carrier connected to the flywheel. Therefore, the ring gear starts rotating in the same direction as the planet carrier and the sun wheel. The vehicle starts moving forwards.

During the pseudo-locking mode the output taken from the flywheel circulates inside the IVT and the energy is being dissipated by its internal resistances. Nevertheless, the IVT output torque $M_{out\ IVT}$ is several times bigger than the CVT output torque $M_{out\ CVT}$ (in a situation where the differential operation is disconnected and when only the CVT is working). The corresponding multiplication factor depends on the efficiency η of the circuit in which the energy circulates.

$$M_{out\ IVT} = M_{out\ CVT} * \eta / (1 - \eta)$$

The multiplication factor of the torque decreases by moving away from the zero transmission ratio, and the energetic efficiency increases. However, it remains significantly worse than without differential linkage.

Therefore, we disconnect the differential linkage after the transmission range depletion towards the slow output rpm. The IVT will, therefore, change into the CVT, which has better efficiency. Before disconnection the ring gear rpm increase to the level of the planet carrier rpm due to the deceleration of the sun wheel rotation (the rpm of the sun wheel and ring wheel equalize) and so the planetary gear set started to revolve as a whole. Consequently, the changeover of the output withdrawal from the sun wheel to the ring wheel runs totally without shock. After the shifting, the CVT transmission ratio starts to return from the slowest value to the quicker values causing the vehicle to accelerate.

Automatic stepped gearboxes present a problem of undesirable alternating up- and downshift at the boundary between adjacent speed gears. Vehicles with combustion engines have solved the problem by shifting up at a higher vehicle speed than for downshift. This is not possible for a gyrobus with mechanical transmission because a shock-free shifting between IVT and CVT is possible only during the slowest CVT transmission ratio. The alternating gearshift mode cannot be totally excluded but the probability of its occurrence is very low. It can only arise when the change of flywheel rpm is exactly identical to the change of the vehicle speed during the slowest CVT transmission ratio. Furthermore, such an alternating gearshift represents no danger for the driving system. Only the driver would notice it and he can easily stop it (a tiny change of power would be enough).

The driver sets the required value of the output torque using the accelerator. The difference between the required and the actual value determines the velocity of the transmission ratio change and, consequently, the flywheel deceleration. The same applies to the brake pedal in the recuperative braking mode when the flywheel accelerates.

Both the driving force and recuperative braking force will be limited by the control system:

- if the maximum value of the CVT torque is achieved,
- if the maximum vehicle speed is achieved,
- if the set maximum output is achieved (so that the vehicle dynamics are not influenced by the level of the flywheel charge).

3.2 Energy recharging

The most important part of the charging station at the terminal are two common three-phase two-poles electromotors with a short-circuit armature, $50/60\ Hz$, $6\ kV$, approx. $150\ kW$, connected to the gyrobus by sheathed articulated shafts. During charging their non-variable rpm are changed into ascending rpm of the flywheel by the same CVTs used to drive the vehicle after moving off (during charging the differential linkage changing CVT into IVT will not be used). Unlike an electrochemical accumulator, the charging accelerates with the increased accumulated energy. The full charging takes 4-5 minutes.

If, exceptionally, it is necessary to start running the flywheel from a total standstill, the external electromotor will also start running from standstill (with Y-connection).

At terminals, the on-board 24 V (or 42 V) LiFePO₄ battery will be charged from an on-board quick-charger connected to the external 220/380 V network together with a quick-charging heat reservoir (approx. 75 kW, 5 kWh) and with the exhauster and air-compressor electromotor.

4 SAFETY OF GYRODRIVE

4.1 Reduction of damages caused by flywheel collapse

With regard to the high circumferential speed of the flywheel (up to 2800 km/h) it is necessary to protect the flywheel box from ruptured fibres (the moment of friction could even release the flywheel box from its attachment). We use a thin ring of carbon laminate which has a little smaller diameter than the flywheel box inside. The pressure of the ruptured fibres extends the ring diameter, so the ring presses on the box and the flywheel decelerates intensively. Graphite coating on the outer surface of the ring reduces the friction coefficient and improves the heat removal. The flywheel deceleration will be more intensive if air is let in.

The kinetic energy 39 MJ of the fully charged flywheel would change 15 liters of 20 °C water into 100 °C steam. Therefore the flywheel box will be surrounded by a housing and through the so created interlayer a coolant will flow.

4.2 Flywheel safety in case of a vehicle accident

The obligatory most severe destructive test of a bus (which applies to a gyrobus) is the overturning test according to Regulation No. 36 ECE. Such an accident represents no danger for the flywheel if situated outside the deformation zone. This Regulation does not require barrier crash tests. With respect to a bus impact into the non-deformable barrier (50 km/h), the specialists' opinion is that the deceleration of the vehicle frame should not exceed 400 m.s⁻² during approx. 50 ms (stopping distance approx. ½ m).

Such a deceleration represents no problem with respect to the flywheel, its box and the attachment to the vehicle frame but the choice of bearings is not straightforward. The energy losses of robust bearings are definitely not negligible. Therefore, relatively small ball-bearings are used, supported by permanent magnets. When a vehicle impact occurs, the floppy part of the flywheel box which houses the outer bearing rings will experience an elastic deformation. Thus, the rotating shaft bears on a robust friction bearing which had not operated before due to large clearance. The calculated shock force of 0.2 MN will require about 150 cm² of sliding surface.

5 ASSUMED MAIN PARAMETERS OF THE GYROBUS DRIVE

The preliminary calculations considered a haul length of 12 km and the energy taken away from two flywheels of a two-axled gyrobus of 78 MJ. At present, composite flywheels achieve a specific energy of 150 kJ/kg (theoretically 673 kJ/kg). So the net mass of two flywheels will be 520 kg (estimated mass of the whole driving system will be about 1200 kg). The power losses of freely rotating flywheels will probably not exceed 0.5 kW and so self-discharging would only present a problem if the drive interruption lasts more than one or two hours. The friction coefficient between the friction members lubricated by a special oil was estimated to be $f = 0.05$ (following the experience of the TOROTRAK company). That reduces the friction losses under the theoretical values shown in figure 9:

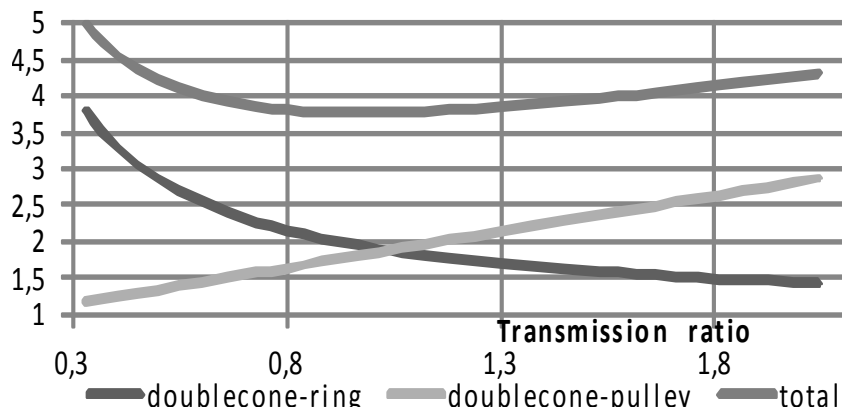


Figure 9: Slip [%] caused by the geometry of friction members rolling

The selected value of the maximum output from the shaft of each flywheel is 110 kW . If it is supposed to be available also at a minimum operating speed of $8400/\text{min}$ (maximum $25000/\text{min}$) then the input torque of the CVT will be 125 N.m (in all other modes it will be lower). With the rpm decreasing to $8400/\text{min}$ each flywheel still hold 4.4 MJ of energy (11.3%), which may be used for a short emergency. Taking the torque 125 N.m into account, the diameter of the IVT box will be about 300 mm .

Even at minimum operating rpm the required maximum vehicle speed is 70 km/h . The corresponding minimum vehicle speed in the CVT mode will be 12.9 km/h (the transmission ratio range according to the drawing is 5.43). With fully charged flywheels it will be 38.4 km/h . In that case or if only little energy is depleted, a slower drive will have to use the IVT mode, consequently with a lower efficiency.

That is why the drive of each rear wheel is equipped with an additional two-speed gearbox. If its low gear ($i \approx 5.5$) is used and the flywheel energy is maximal, already at approx. 7 km/h the less economical mode IVT will be changed to the more economical mode CVT. When the speed exceeds 39 km/h , the high gear ($i = 1$) will be used.

Gear shifting is not simultaneous for both drives of rear wheels. Transmission ratio of one drive is changed at a lower speed than of the other. If shifted, the driving force is interrupted and therefore the torque for the drive other wheel is boosted (controlled by ASR).

The planetary gear set turning a CVT into an IVT (in the differential mode) has wheels with a number of teeth in the ratio of $t_s : t_c : t_r = 14 : 24 : 62$ (the indexes mean: s... sun gear, c... carrier, r... ring gear).

The draft has used rough calculations only. The following problems have not been solved at all:

- providing for a pressure balance of parallel disks on the double-cones,
- a concept of a comprehensive control system, including a sensor for load torque,
- transmission scheme for charging,
- heat removal.

6. EXPECTED ADVANTAGES

- A cost-saving when substituting city buses with equally flexible zero emission vehicles;
- Reduced operating costs for routes where the substitution has been implemented;
- The possibility of utilizing the developed IVT also in other areas (e.g. ground machines, military vehicles, trucks etc).
- A more economical use of non-renewable sources (for example, in the Czech Republic almost 30,000 tonnes of diesel fuel could be saved annually).

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