The Ikona Clutch and Differential

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Abstract

This paper describes two devices—a clutch and a differential—which are based on the Ikona continuously variable transmission (CVT). This CVT is essentially an internal gear pair, in which the pinion is mounted on an eccentric that can drive or be driven by an electric motor/generator, thus providing a variable ratio. Since this arrangement allows for "branching" of energy flow, it can be classified as summation-type CVT. The range of ratios depends on the input speed. For example, with an input speed of 600–2,000 rpm, the ratio can be anything from infinite to about 1:2.

When the CVT is used as a clutch, it would replace the friction-plate clutch in vehicles with standard transmissions, and the fluid torque converter in automatic transmissions. In these existing devices, energy is wasted during modulation from standstill, and at every gear change, while the engine speed is altered to match the speed of the gearbox input shaft. In the case of the fluid torque converter, energy is also lost during acceleration, due to the inefficiency of the device whenever the engine speed differs from the speed of the converter output shaft. The new clutch will be referred to as the electric torque converter. Any excess energy is converted into electrical energy, and either stored in the battery, or reintroduced into the system through the motor/generator. With very efficient energy recovery, modulation of the clutch can be very smooth, which is particularly advantageous when a vehicle starts from rest on an uphill slope. Since no friction element is involved, and only a fraction of torque is being manipulated, the modulation can be repeatable regardless of conditions. Finally, in a hybrid vehicle arrangement, the clutch can be used to maintain the engine at its optimum speed (within limits), regardless of the road speed and the gearbox ratio.

Similar principles apply to the Ikona differential. Unlike today's limited slip differentials, the Ikona differential allows full torque to be transmitted through one drive wheel, even though the other drive wheel may have completely lost traction. Unlike traditional differentials that allow wheels to rotate at different speeds, the Ikona differential forces the wheels to do so. Accordingly, when the vehicle is changing direction, the differential can be used to control the speed of each drive wheel, thus providing active torque steering.

Introduction

The Ikona CVT consists of an internal gear pair, in which the pinion is mounted on an eccentric, as shown in Figure 1. The eccentric is connected to an electric motor/generator, whose speed can be modulated, thus providing the variable ratio. The CVT can be used as a clutch (Fig. 2), replacing the plate clutch in a standard transmission, or the fluid torque converter in an automatic transmission. When the CVT is used in this manner, it will be called an electric torque converter.

The CVT can also be adapted to form a differential (Fig. 3).

In this case the internal gear is meshed with two pinions, each mounted on separate eccentrics, so there are two outputs with independently controllable ratios. The electric torque converter and the differential are the subjects of U.S. provisional patent applications 577088002 pro and 577088003 pro.

Description of the CVT Clutch/Electric Torque Converter

The Ikona gear is an internal gear pair, described in patents US5505668 and EP770192B1. Compared with conventional involute gear pairs, it has the following advantages. First, the difference between the tooth numbers can be as low as one. Secondly, the contact ratio is high, meaning that a gear pair can transmit a larger torque than an involute gear pair of similar size. Thirdly, the backlash is minimal. All these properties are important when the gear pair is used to form a CVT.

Along similar principles, a solar epicyclic gear system can be used, in which case the following has to be satisfied:

$$(N_{ring}/N_{sun}) * \omega_{in} = (1 + N_{ring}/N_{sun}) * \omega_{out} - \omega_{sun}$$

where

N_{ring} and N_{sun} represent the number of teeth on the ring gear and sun-pinion respectively, ω_{in}, ω_{out} and ω_{sun} stand for rotational speeds of flywheel, output shaft and sun-pinion, respectively. This embodiment may be referred to as the Solar CVT Clutch. More detailed analysis of this type of arrangement may be the subject of another paper.

When the CVT is used as a clutch/electric torque converter, the internal gear is connected to the engine output—generally the flywheel—and the pinion is connected to the input shaft of the gearbox. The pinion and internal gear tooth numbers will depend on engine and vehicle properties; for the purpose of this paper we may work with those numbers being respectively 19 and 20. This means that the geometrical clutch input/output ratio would be 20:19, (i.e., close to 1.0:1) if the eccentric were held stationary. However, for the situation where the eccentric is allowed to rotate around its own axis, the relation between the input, output and eccentric angular velocities is given by:

$$20 * \omega_{int} = 19 * \omega_{pinion} + \omega_{ecc} \tag{1}$$

where ω_{int}, ω_{pinion} and ω_{ecc} are the three angular velocities.

When solved for the transmission input speed, Equation 1 becomes:

$$\omega_{pinion} = \frac{(20 * \omega_{int} - \omega_{ecc})}{19} \tag{2}$$

When solved for ω_{ecc}, for case $\omega_{pinion} = 0$, equation (2) becomes:

$$\omega_{ecc} = 20 * \omega_{int} \tag{3}$$

The input and output torques T_{int} and T_{pinion} are related to the eccentric torque T_{ecc} as follows (*note: torque equations do not consider internal losses*):

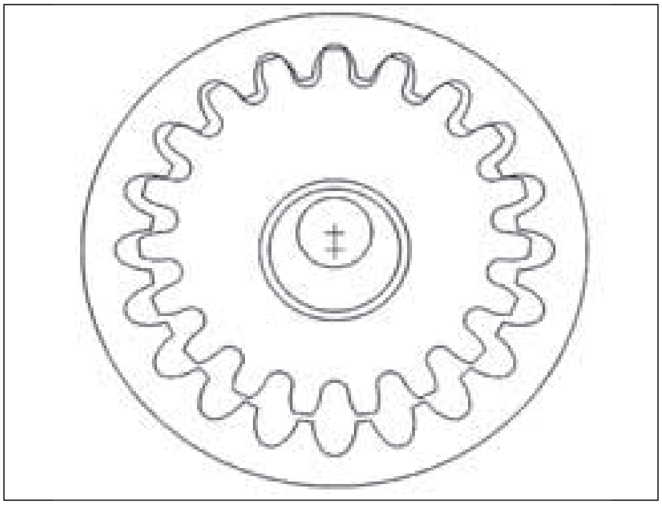

Figure 1—Ikona CVT.

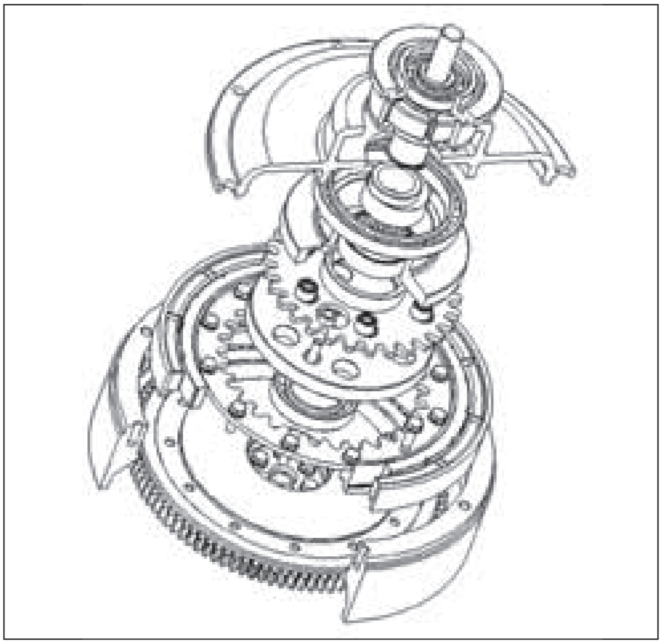

Figure 2—Sectional exploded view of Ikona CVT clutch.

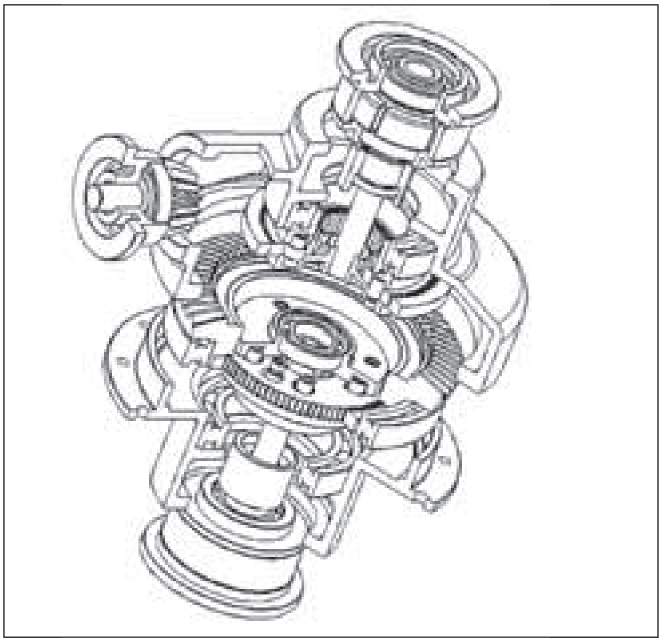

Figure 3—Sectional exploded view of Ikona CVT differential.

$$T_{int} = 20 * T_{ecc} \quad (4)$$

$$T_{pinion} = 19 * T_{ecc} \quad (5)$$

Looking at Equations 1–5, we may find that:

- It is possible to keep the transmission input shaft stationary ($\omega_{pinion} = 0$) while the engine is running ($\omega_{int} \neq 0$).
- In order to provide this condition, the eccentric needs to spin at 20 times engine speed ($\omega_{ecc} = 20*\omega_{int}$ for 19/20 teeth combination).
- By modulating the eccentric speed from $\omega_{ecc} = 20*\omega_{int}$ to $\omega_{ecc} = 0$, we can achieve transmission input shaft modulation from $\omega_{pinion} = 0$ to $\omega_{pinion} = (20/19)*\omega_{int}$.
- Modulation of the transmission input torque from $T= 0$ to $T = T_{nominal}$ can be achieved by manipulation of the eccentric torque, which represents only 1/19 of T_{pinion} (1/20 of T_{int}).

In all vehicles, the engine speed will differ from the gearbox input shaft speed when the vehicle starts from rest, and during and immediately after each gear change. In addition, in vehicles with automatic transmissions, the torque converter will allow the engine to turn faster than the gearbox input shaft during acceleration in order to provide smooth running and more torque.

The process of speeding up the output shaft of a clutch and matching its speed to the input shaft (flywheel) is called clutch modulation. The power of modulation at any given moment can be calculated by:

$$P = T_{eng} * \omega_{eng} - T_{gboxinput} * \omega_{gboxinput} \quad (6)$$

While the exact values of T_{eng} and $T_{gboxinput}$ may not be known, it is clear that there is excess power from the engine during the situations listed above. The total energy of modulation will then be given by:

$$E = \int_{t_1}^{t_2} P * d_t \quad (7)$$

Obviously, in systems with single-energy path, the energy of modulation will be released within the clutch/converter. In order to prevent overheating and/or premature wear on these devices, both power and duration of modulation need to be limited. This, in turn, may lead to shock-loading other components of the drivetrain and/or to an uncomfortable ride in the vehicle. An alternate solution is to provide an auxiliary branch in the energy path and to direct the energy of modulation through that auxiliary branch. Ideally, we may convert that energy into useful work or store it in another form for future use, thus minimizing waste and improving efficiency.

In the Ikona CVT clutch, the difference between the speeds of the engine and the gearbox input shaft is accommodated by the CVT gear pair and the rotation of the eccentric. The energy of modulation is used to spin the eccentric, which drives the motor/ generator attached to it. (In spinning the eccentric to alter the ratio between the engine speed and the gearbox input speed, the motor/generator will be referred to as a modulating motor/generator.) This energy is then converted into electrical energy, which is fed into the vehicle battery. In cases where extra energy is required, as we will see shortly, the energy is fed from the battery into the motor/generator, which then acts as a motor and adds to the engine torque.

For example, when the vehicle starts from rest, the eccentric will be turned initially at 20 times the engine speed, so that the vehicle remains stationary, as seen in Equation 2. For many vehicles, the idle speed of the engine would be about 700–900 rpm, so the eccentric would be controlled to turn at 14,000–18,000 rpm. However, it is often advantageous to increase the engine speed when starting from rest, particularly for heavy commercial vehicles when starting on an uphill slope, in order to prevent stalling. The engine speed can be increased to about 1,500–2,000 rpm before the vehicle moves, thus providing greater torque, and the eccentric would then be controlled to turn at 30,000–40,000 rpm. This is a high speed for the modulating motor/generator, but not unattainable. Many modern electric motors, with permanent magnets and in the 10 kW range, are in fact most efficient at speeds of 30,000–40,000 rpm, and the eccentric would only turn at these high speeds for very short periods of time.

To accelerate the vehicle from zero speed until the gearbox changes from first to second gear, one need only reduce the speed of the eccentric, which can be easily and repeatedly done by loading the modulating motor/generator. As seen in Equation 4, the torque required for the eccentric is only equal to the engine torque divided by 20, so this is quite practical. Finally, electric motors/generators typically provide torque curves that are perfectly suited for this kind of duty.

When the eccentric is not turning, we can see from Equation 1 that the (synchronous) engine speed is equal to the gearbox input shaft speed, multiplied by 19/20. If the engine turns faster than the synchronous speed, the eccentric must rotate in the same direction as the engine. If the engine turns slower, the eccentric must rotate in the opposite direction.

When the engine is driving the vehicle, and the eccentric turns in the same direction as the engine, we can show by a simple force analysis that the eccentric will drive the modulating motor/generator so that electric energy will be fed into the vehicle battery. If the eccentric turns in the direction opposite to the engine, the eccentric will need to be driven by the motor/generator so that energy is drained from the battery.

If the vehicle is driving the engine—e.g., on a steep downhill slope—the engine torque is reversed. In this case the eccentric will be driven by the motor/generator when it turns in the same direction as the engine, and will drive the modulating motor/generator when it turns in the opposite direction.

These conclusions enable us to determine the flow of energy in various phases of the vehicle motion.

In spinning the eccentric to alter the ratio between the engine speed and the gearbox input speed, the motor/generator will be referred to as a modulating motor/generator. For example, when the vehicle starts from rest, the engine speed is faster than the synchronous speed, so the eccentric turns in the same direction as the engine, and the generator feeds energy into the vehicle battery.

The situation is similar whenever there is an upward change of gear. Immediately after the gear change, the engine is turning faster than the synchronous speed; to allow for the different speeds, the eccentric must be rotated in the same direction as the engine, so the eccentric will again drive the generator, and energy will be fed into the battery.

On a downhill slope, or when the vehicle is slowing down, the accelerator pedal is released and we have engine braking. The engine speed is then less than the synchronous speed, so the eccentric turns in the direction opposite to the engine; but since the engine torque is reversed, the eccentric will once again drive the generator, feeding energy into the battery.

The last case to be considered is the downward change of gear. There are generally two possible reasons for downward gear change.

The first is that the vehicle is slowing down preparing to stop. If the engine was turning at synchronous speed before the gear change, it will be turning at less than the synchronous speed immediately after. As the vehicle slows down the engine torque is again reversed, and the eccentric will again drive the generator.

The second reason for a downward gear change is that the accelerator pedal is depressed, either to provide acceleration or because the vehicle is traveling uphill. In this case, the downward gear change causes the speed of the gearbox input shaft to increase, so that immediately after the gear change the engine is turning at less than the synchronous speed. The eccentric is then turning in the direction opposite to the engine, and must be driven by the motor. This is the one situation where energy is required from the battery. As compensation, the extra power exerted by the electric motor helps the vehicle to accelerate, or to maintain its speed up an incline.

In summary, in most instances where energy is wasted by conventional clutches or fluid torque converters, the Ikona CVT clutch uses that energy to drive the modulating motor/generator, thus charging the battery. In the one situation where the Ikona CVT clutch draws power from the battery, this power is used to improve the performance of the vehicle. It is important to note, however, that in the form described, drawing energy from the battery increases the power going into the gearbox, but leaves the gearbox input torque unchanged. The input torque to the gearbox is related to the engine torque by Equations 4 and 5:

$$T_{pinion} = T_{int} \cdot \left(\frac{19}{20}\right) \tag{8}$$

The spinning eccentric allows the gearbox input speed to turn faster than the synchronous speed, and since the torque remains constant, the gearbox input power is increased. This is now higher than the engine output power, and the difference is made up by the power drawn from the battery.

In order to increase the torque availability and reduce the number of times energy is converted from one form to another (efficiency issues), another electrical machine may be integrated in line with the main torque path (flywheel, ring gear). This machine is called the converting motor/generator. By this addition, any electricity generated in the modulating generator may be directly used within the converting motor, thus increasing torque available to the clutch and reducing the number of energy conversions. The end result of this process is similar to that achieved with fluid torque converters, albeit with better overall efficiency and a few extra features possible. The converting motor/generator may offer several other opportunities for improved performance and economy, many of those being applied in modern hybrid (ICE-electrical) vehicles.

To sum up, the Ikona CVT clutch/electric torque converter offers several significant advantages over the traditional, friction plate clutches and fluid torque converters in that:

- The speed of the eccentric can be repeatedly modulated by the controlling computer, so that every gear change, and the starting from rest, will be completely smooth.
- Energy of modulation normally lost to heat and wear, is recovered in the form of electricity.
- The size of the CVT clutch/electric torque converter will be considerably less than that of the plate clutch or the fluid torque converter, which it replaces. This is because of the high contact ratio of the Ikona gear pair, mentioned earlier, which reduces the size of the gear pair required to transmit the engine torque.
- It may be possible to control the eccentric speed so that the engine turns most of the time at or near its most efficient speed, regardless of the vehicle speed or gearbox ratio. This feature would probably require more continuous energy interchange with the battery than the other advantages described above. It is therefore more suitable for hybrid vehicles, where the battery capacities are much larger.
- The CVT clutch/electric torque converter may replace starter-motors and alternators thus further improving on cost, ease of packaging and mechanical complexity.

Description of the differential

The layout of the Ikona CVT used as a differential is essentially the same as that shown in Figure 1. The only difference is that the internal gear is meshed with two pinions, and each pinion is mounted on its own eccentric. In a rear-wheel-drive vehicle, the internal gear would be attached to the hypoid gear, while in a front-wheel-drive, it would be attached to the gearbox output shaft. Each pinion would drive one of the vehicle wheels. (If used as center differential for AWD or 4WD vehicles, each pinion would drive an input to axle differentials.)

When a vehicle rounds a corner, the driving wheels must turn at different speeds, in order to avoid extreme tire wear. A conventional differential allows the drive shafts to turn at dif-

continued

ferent speeds, with the average speed equal to the differential input speed, and the torques in the two output shafts being equal. A problem with this device occurs if one wheel loses traction, for example when it rests on ice. The torque on this wheel falls to zero, causing the torque on the other driving wheel also to become zero. The second wheel stops turning, and the first wheel turns at twice the speed of the differential input.

This problem is partly avoided by the use of a limited slip differential. In this case, when the first wheel loses traction and starts to spin, a reduced torque is maintained on the second wheel, sometimes by the use of a plate clutch. When a vehicle is in motion, this reduced torque is generally enough to continue the motion. But for a vehicle starting from rest, the torque may not be enough to start the vehicle, when one wheel has lost its traction.

In the Ikona differential, the speed of each output shaft is determined by the speed of the corresponding eccentric, and these are controlled separately by the vehicle computer. If the gear pair has N_{pinion} and N_{int} teeth, and the eccentrics do not turn, then the differential output shafts will rotate at the speed of the differential input multiplied by (N_{int}/N_{pinion}). Since the speed differential between any two wheels or axles on a vehicle is, typically, very low, we can afford high tooth count in the pinion and ring gear, thus minimizing the torque required on the eccentric. For illustration purposes, a mid-size vehicle traveling at 100 km/h only requires 200–250 rpm speed differential between the right and left side wheels for full steering input (under 11 m turning circle). If we work with 20,000 rpm maximum motor/generator (eccentric) speed, this translates into 79/80 tooth combination. This further means that the motor/generator only needs to be capable of less than 2 percent of the total torque being transmitted.

As before, this speed is called the synchronous output speed. In straight vehicle motion, the output shafts will both turn at the synchronous speed. When the vehicle turns, the computer could be programmed to allow the shafts to turn at their natural speeds, which depend on the vehicle speed and the radius of the vehicle path. However, this differential has an important advantage over conventional differentials. The computer will be programmed to control the eccentric speeds, so that the wheels are forced to turn at the correct speeds, corresponding to the vehicle speed and the radius of its path. This feature of the differential provides active torque steering.

A second advantage of the Ikona differential is its response when one wheel loses traction. The torque applied to this wheel will fall to zero, but there is no reason why the wheel should start to spin, since its speed is controlled by the speeds of the differential input and the eccentric. If the position of the accelerator pedal is unchanged, both wheels will continue to turn at the same speeds they had before the first wheel lost its traction. And the entire torque from the differential input will then be transmitted to the second drive wheel, which means its torque will double in magnitude.

In conclusion, the Ikona CVT differential offers several advantages over the traditional, open, limited slip and locking differentials:

- Instead of merely allowing different wheel speeds through torque equality, it enables us to impose a desired speed to each powered wheel individually.
- It allows improved vehicle stability through active torque steering capability.
- It allows vehicle steering even without controlling the direction of steering wheels; it is applicable to track vehicles.
- When applied to track vehicles, it allows improved performance and fuel economy through recovering energy normally lost to friction braking.

Summary

The Ikona tooth form has received recognition for its suitability in high-ratio, cycloid-type reduction units. As with all units utilizing cycloid architecture, the high ratio is achieved between the eccentric and either the pinion (wave plate on SM Cyclo and equivalents) or the ring gear (pin housing on SM Cyclo and equivalents). It is very important to note that, providing the eccentric is restrained from rotation, the ratio between the ring gear and the pinion is near 1:1, which makes it suitable for "coupling" application. (As a general rule, we need to work with the highest tooth count practical, since this will allow us the lowest eccentric torque for any given application.) When used as such, and by allowing the eccentric to rotate in a controlled manner, we effectively create a CVT coupling suitable for speed modulation.

The Ikona CVT can be used as the basis of a clutch and of a differential. In both cases, these new devices have considerable advantages over existing clutches and differentials, the most notable ones being:

- Utilization of energy normally lost to heat
- Controllability
- Repeatability

Ikona CVT-based clutches, torque converters and differentials can become active, rather than passive, members of any vehicle, greatly contributing to vehicle efficiency, dynamics and safety.

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