

Development and Challenges of Electrically Selectable One-Way Clutches

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ABSTRACT

This paper discusses new developments in the field of one-way clutches (OWC). These recent developments involve “Selectable OWC (SOWC)” actuating both hydraulically as well as electrically. The primary focus of this paper is a low-current consuming Electrical SOWC (eSOWC) used in hybrid transmission being designed and developed at Ford Motor Company. Other SOWCs currently being utilized across different applications at Ford are also discussed. Clutching devices represent significant cost, weight, size and drag-loss in automatic transmissions. However, implementation of SOWCs offers the potential to reduce transmission cost, size, weight, and spin loss; eSOWCs may also improve shift quality, reduce shift times, improve shift consistency and reduce OWC-related NVH. In Hybrid applications the electric motor(s) and SOWC create a system that is analogous to a manual transmission synchronizer. Similarly, in automatic transmissions SOWC are analogous to pump-solenoid-valve-friction-clutch system. In conclusion, this paper is intended to educate the reader on the development challenges and benefits associated with SOWC using analytical and empirical data.

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INTRODUCTION

There are three kinds of switching elements used in automatic transmissions. Clutches may be dry or wet type friction clutches, where wet type clutches are most commonly used in automatic transmissions. One-Way Clutches (OWC) are also commonly used in automatic transmissions. Selectable OWCs (SOWC) are a new kind of switching elements in automatic transmission.

SOWCs have numerous benefits over traditional friction clutches. In the low/reverse position they save space, reduce spin loss, reduce complexity, and reduces cost. In Hybrid transmissions SOWC provide significant improvement in fuel economy without the negatives associated with traditional friction clutch systems. This paper will attempt to discuss the benefits as well as the challenges of implementing SOWC.

Clutches

A “Clutch” is a device that is used to mechanically connect and disconnect machine elements. A clutch either transfers torque in both clockwise (CW) and counter-clockwise (CCW) direction, or neither direction. Also, it is a device that requires active control.

Clutches have the ability to slip. During their transition from open and not transferring torque to clamped and transferring torque, the clamp load can be modulated to force the clutch to transfer only part of the applied torque. This can be a blessing when trying to achieve a smooth shift. It can also be a curse as the friction plate(s) wear and lose their ability to transfer torque. If slip is not properly managed heat can buildup and damage the friction material. Proper level of slip is very important to smooth shifts in automobiles.

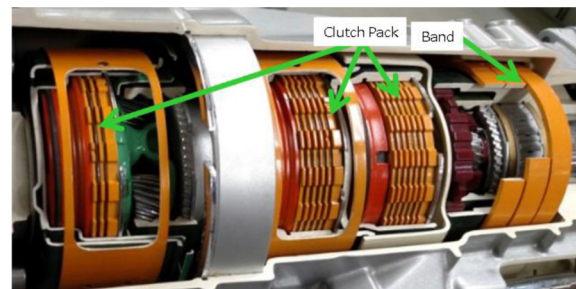


Figure 1. Cutaway of automatic transmission showing 4 wet friction clutches.

An automotive manual transmission has a clutch between the engine and transmission that is typically pedal-operated by the vehicle driver. Depress the pedal and the engine and transmission are disconnected, so engine power cannot get to the drive wheels. When the driver takes their foot off the pedal the engine and transmission are connected so engine power is applied to the drive wheels. In this example, if the pedal is released poorly, the vehicle may lurch, jerk, spin the tires, or stall the engine. Inexperienced drivers may struggle to learn how to coordinate all that goes into making a smooth engagement.

One-Way Clutches

One-Way Clutches (OWC) are devices used to mechanically connect and disconnect machine elements. An OWC transfers torque in one direction (for instance, only CW) and does not transfer torque in the other direction (for instance, CCW). An OWC does not require or have active control. One way clutches are not typically designed to slip, they transition from freewheeling to lockup rapidly. OWC can be Friction type or Ratchet type.

OWC do not have the ability to slip when functioning properly. Where a clutch is like an analog device, able to partially transfer torque, a OWC is like a binary device, it is transferring torque or not transferring torque. Roller and sprag OWC can slip, but this is generally associated with failure. Ratcheting OWC cannot slip, they either engage and carry torque or they do not. OWC also tend to change state very rapidly, generally between 5-50 milliseconds. The combination of their binary nature and how rapidly they change state can lead to negative shift quality (commonly “clunks” or “bumps”). For instance, in one of the Ford’s six-speed rear wheel drive transmission, 6R80, if the friction clutch brake CB26 is unclamped too rapidly, the shift from second to first gear will be harsh as torque reaction is transferred too quickly from the CB26 friction clutch to the L/R OWC. Structural information about Ford’s 6R80 transmission is provided in [Appendix A](#).



Figure 4. Mechanical Diode.



Figure 2. Roller OWC.



Figure 5. Rocker OWC.

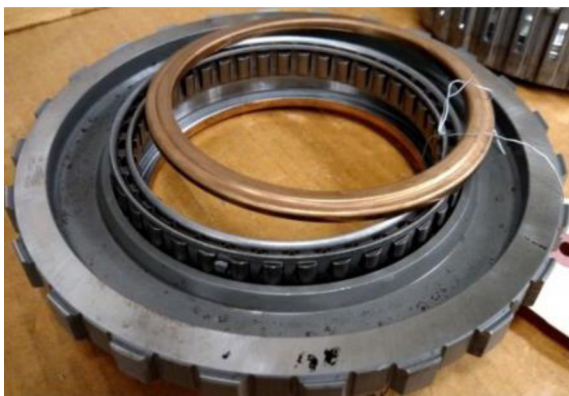


Figure 3. Sprag OWC.

Examples of OWC that rely on “Pawls” and ratchet are Mechanical Diodes and Rockers.

Early use of OWC in transportation starts with bicycles. The Smithsonian website provides information that Mr. William Van Anden patented an OWC for use in a bicycle in 1869 [1]. This revolutionary bicycle allowed the rider to coast forward without having to move their legs. It is interesting to note that the OWC was a ratcheting type, not a friction type. Most bicycle ratchets follow Mr. Van Anden’s 1869 design and layout.

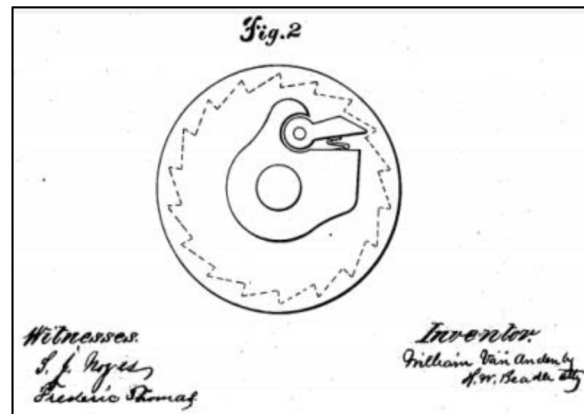


Figure 6. Mr. Van Anden’s art from 1869 patent 88238. Cam is outer race (wheel) and pocket is part of axle. A survey of the current bicycle industry shows most freewheels use this arrangement to this day. [2]

The earliest use of OWC in automobiles is for the starting system. Kettering receives credit for first implementation of an electric starting system in 1910-1912 General Motors vehicles. His system used a roller OWC in the electric starting motor. Like Van Anden’s system with bicycles, a survey of starting motors today shows the roller OWC sub-system has not changed since Kettering finished his work. Starting system OWC clearly existed prior to Kettering’s work.

The McMullen's devised a ratcheting system used in the starting system as early as 1902. It is interesting that ratchet type OWC predate friction type OWC in automotive use. [4]

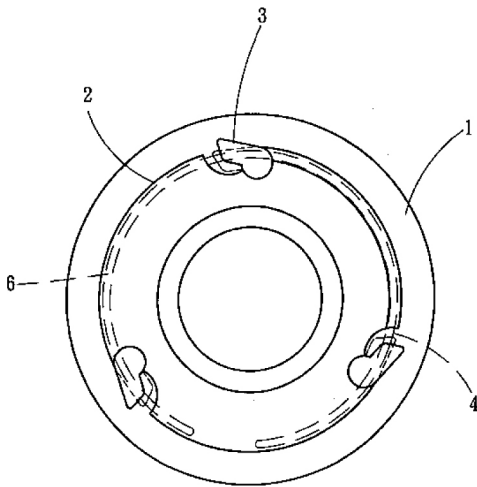


Figure 7. Mr. Chun-Hsung Chen's art from 2005 patent US20050139443A1. This freewheel follows Mr. Van Anden's arrangement from 1869. [3]

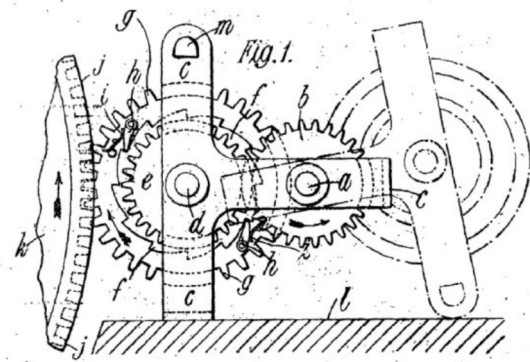


Figure 8. Mr. John Alexander McMullen and Kenric James McMullen's starter disconnect patent GB190200298A. [4]

In 1948 GM released the "Dynaflow" transmission that is considered the first true automatic transmission. The Dynaflow was first used in the M18 Hellcat tank, then applied in the Buick Roadmaster. The Dynaflow torque converter had roller-type OWC in it. [5]

Roller and Sprag OWC were used in automatic transmissions. The Ford C4, a three speed transmission, introduced in 1964, used a roller OWC designed in the spring and summer of 1962. Later automotive uses of OWC include seatbelt ratchets and front end accessory drives.

OWC are widely used in automotive automatic transmissions to improve shift quality and make tuning the wet friction systems in the transmission easier. In an automatic transmission OWC are frequently one of the clutches that are used to couple elements for first gear ratio. For instance, in 6R80 transmission, a friction clutch, the C1234, and an OWC, the "L/R" OWC are both transferring torque to create first gear. The C1234 is the input into the rear Ravineaux planetary system's Sun #3, the L/R OWC grounds the Ravineaux carrier to the case, and the ring gear carries torque out of the transmission. To shift to second gear, the transmission applies the CB26. As the CB26

friction pack is clamped the planetary reaction is transferred from the OWC to the CB26. This causes the Ravineaux planetary system's Sun #2 starts to become the reaction instead of the carrier. This reverses the direction of torque on the Ravineaux carrier. As the direction of applied torque on the Ravineaux carrier reverses, the L/R OWC state goes from Lockup to Freewheel.

The use of an OWC means that only one friction clutch must be actively controlled to change gears. If a friction clutch might be used instead, to change from first to second gear the control system would need to synchronize the release of the CB1R friction pack and the application of the CB26 friction pack. Achieving a smooth shift between 2 friction packs can be challenging, and the challenge increases in lower gears due to larger step sizes between gears.

Selectable One-Way Clutches

Recently the auto industry has seen the introduction of "Selectable" OWC (SOWC). Selectable OWC connect machine elements. A SOWC may transfer torque in neither direction, either direction, or both directions depending on the configuration. A SOWC may require active control of some elements and may not require active control of some elements. Existing SOWC designs may make use of hydraulics as a power source, or electricity.

SOWC do not have the ability to slip when functioning properly. Depending on the design of the SOWC, the time between freewheel and lockup may vary significantly. SOWC may have issues with NVH (clunks or bumps). Because SOWC do not slip, they also have potential for being damaged during actively commanded transitions from freewheel to lockup.

One type of SOWC could be a single active OWC. The outer race would be attached to a rotating member and would contain the pawls. The inner race would be fixed to the transmission case and contain the cams. The inner race would also contain a coil that when energized would cause the cams to attract the pawls. In this arrangement, the SOWC becomes a type of solenoid, and the pawl becomes an armature.

Ford has designed a Rocker-type SOWC that uses an electromagnetic element in the cam plate to attract the pawls housed in the pocket plate to engage and transfer torque between raceways. This design, when electrical power is off, allow freewheeling in both directions. As the raceways never make contact, drag losses are very small. When electrical power is on, this design will lock in one direction and ratchet in the other direction.

The comparison of Clutches, One-Way Clutches, and Selectable One-Way Clutches shows that there is some commonality between the three types of devices, and some notable differences. Machine element disconnection & re-connection, direction(s) of torque transfer and direction(s) of freewheeling, need for active control, and type of activation energy need to be considered when choosing a device for specific applications.

Benefits

There are many benefits to SOWC. In the low/reverse position they save space, reduce spin loss, reduce complexity, and reduces cost. Another benefit is that the selectable OWC sets up a significant change in the design of the overall transmission.

Friction clutches require axial space for the piston to stroke, typically 5-7 millimeters. This stroke is in addition to the space for the many friction plates needed for torque capacity. Rather than transfer torque through wood as is the case with friction clutches, OWC transfer torque through metal. It should be obvious why OWC require less total volume to carry an equal torque to a system that includes wood as it's structural element.

Ford has measured spin loss of low/reverse friction systems of 0.7 Nm - 6.5 Nm. The SOWC spin loss is less than 0.1 Nm. Because the SOWC raceways do not touch, the spin loss is not large enough to be measured. Therefore, spin loss is reported as lower than the resolveable value of the measuring equipment.

The complexity of a single friction clutch is greater than a SOWC. A friction clutch in a modern automatic transmission has in it's parts list a solenoid, a valve, wormtrails, cushion plate, friction plates, separator plates, pressure plate, multiple snaprings, belleville spring (or coil springpack), piston and seals, balance dam and seals. The SOWC shown in [Figure 9](#) has fewer components.

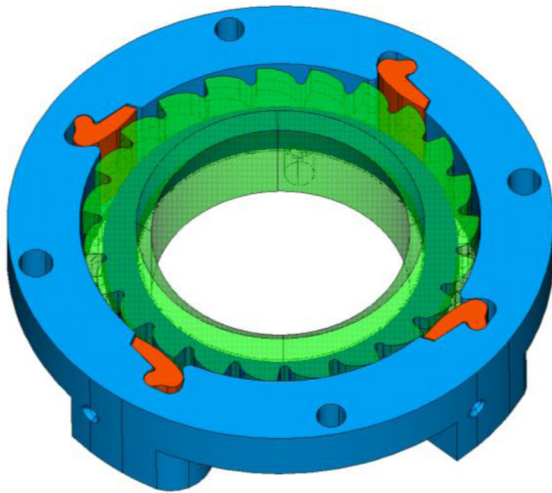


Figure 9. Ford eSOWC. Blue race rotates and contains pawls ("rockers"). Green race is static and contains an electromagnetic coil to selectively magnetize the raceway. The pawl is the armature, and is attracted to the green inner raceway.

Currently automatic transmissions are designed much the same way as the original 1948 Dynaflo design. Automatic transmissions have hydraulic pumps, not merely oil pumps. These hydraulic pumps are capable of pressures exceeding 300psi. These pumps are consuming energy if the vehicle motor is running. These pumps are required to serve the torque converter and provide the forces necessary to clamp the clutch packs. Clutch packs can require 2,000 pounds or more of axial clamping force (Ford 6R80 Low/Reverse clutch @ 228.5 psi has 2,084 pounds of hydraulic force exerted on piston). Together, the pump, torque converter, and clutches consume significant energy.

Elimination of these systems from automatic transmissions, while maintaining or improving both performance and metrics such as shift feel, could result in a more efficient transmission.

A comparison of the energy consumed by a hydraulic pump that clamps friction packs to the Hybrid electrical SOWC gives a sense of the difference in energy consumed. Using the formula;

$$P = \frac{(q * p * g * h * n)}{3.6 \times 10^6}$$

P = power, kilowatt

q = flow capacity, 0.6 cubic meters per hour

p = fluid density, 0.846 kilograms per cubic meter

g = gravity, 9.81 meters per square seconds

h = differential head, 56 meters

n = efficiency, 0.8

In a 5.5 hours drive (Detroit, MI to Lexington, KY), 1,900,000 joules of energy is consumed. This equates to 0.05 gallons of gasoline burned if 125,000,000 joules per gallon of gasoline is assumed, and 30% efficiency is assumed for the engine.

The SOWC operates on 12 volts. It is turned on with a 500 millisecond pulse of 1.5 amps of electrical energy. It is possible to travel non-stop between Detroit and Lexington. In this scenario, the SOWC consumes 9 joules of energy. If the batteries had been charged, the SOWC would have no effect on gasoline usage. Many people prefer not to drive for 5.5 hours non-stop, and traffic and construction will more likely than not slow a vehicle, so this scenario is optimistic. However, the point that a hydraulic pump consumes more energy than a low power pulsed electrical device seems clear. When combined with the spin loss comparison of friction clutches to SOWC earlier in this paper, it should be clear that from an efficiency point of view, SOWC are more efficient than traditional hydraulic pump & friction clutch systems.

ELECTRICAL SOWC

Background

A new generation power-split hybrid transmission is being developed at Ford Motor Company. This transmission continues to make use of planetary gearset as power-split device but it has an added feature of grounding the generator rotor attached to the sun gear of planetary gearset. Grounding the generator rotor or sun gear locks the gear train in a fixed engine-to-wheels ratio. In this case transmission essentially operates similar to a parallel hybrid mode implying engine and traction motor supply power to wheels together.

The main advantage of doing this lies in the fact that generator losses are eliminated since the generator is not spinning. Secondly, the traction motor can spin unpowered at speeds higher than maximum controlled speed enabling higher max vehicle speed. Eliminating