UTIMATE
TRANSMISSIONS

TECHNOLOGY 3

Direct Roller Steering
DRS

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Overview of Toroidal Variator Ratio Control

The control of Toroidal Variators all involve rotating the rollers so that the relationship of the input and output contact points with respect to the axis of rotation of the discs vary

A unique feature of Toroidal Variators is that the rollers can be steered to new ratios so that no actual force is required to move them from ratio to ratio. The rollers are turned like the front wheels of a car and “steer” across the faces of the input and output discs, to a new ratio. They are not normally required to “slide” sideways over the surface of the discs.

In this way the rate of ratio change can be very fast and requires little energy to execute.

This sets them apart from the belt and chain type CVT’s which require actual sliding resulting in higher forces, slower ratio changes, significantly more energy loss, and possibly greater wear rates. Both Torotrak (SFTV) and NSK (SHTV) use this steering method of control while CVTCorp does not.

Torotrak and NSK use different methods to create the ratio change.

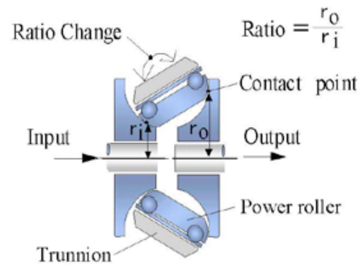


Fig.2 Ratio change principle

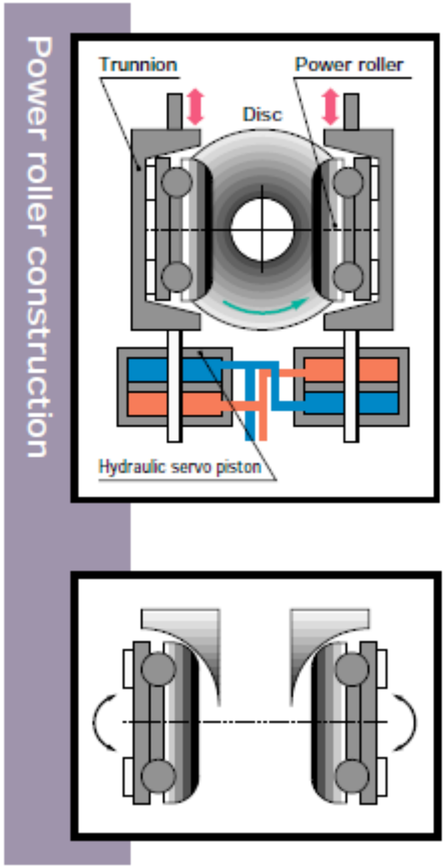
When the input contact point is close to the axis and the output contact point is a long way from it the CVT is in a Low Gear. When this is reversed it is in a High Gear. When it is in the centre it is in a 1:1 gear with the input RPM matching the output RPM.

This diagram explains ratio control for a SHTV – the arrangement is similar for the SFTV without the need for thrust bearings.

Ratio Control of SHTV

The Single Half Toroidal variator is controlled using a steering method that allows for the execution of very rapid ratio changes

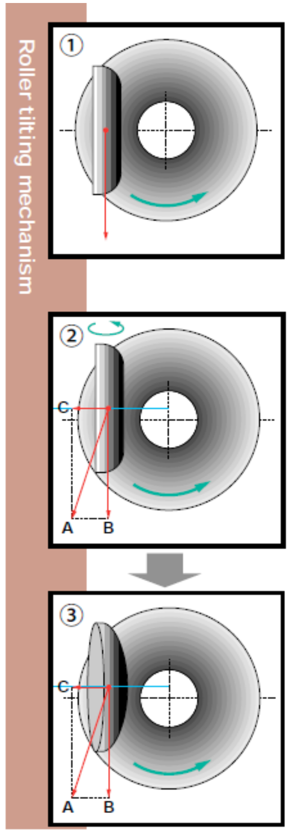
The diagram below explains how this action occurs in a SHTV. This diagram is taken from an NSK paper explaining the steering control in an Extroid Variator.



A power roller is supported above and below by a support called a trunnion. The entire assembly is connected to a hydraulic servo piston that moves the assembly up and down.

The power rollers are constructed so that they move in the direction of rotation centered around the trunnions.

When the rollers are moved forward or backward by the action of the servo piston they become subject to a rotating force and steer to a new ratio position.



When the axis of a power roller passes the center of the disc, force for tilting the roller is not generated. Consequently, since the tilt of the roller remains the same, no ratio change is executed.

When the axis of a power roller moves upward, the force (A) transmitted from the input disc produces force (B) that rotates the roller and force (C) that acts to push the roller toward the outside. This latter force (C) tilts the power roller around the center of the trunnion axis.

Ratio Control of SHTV

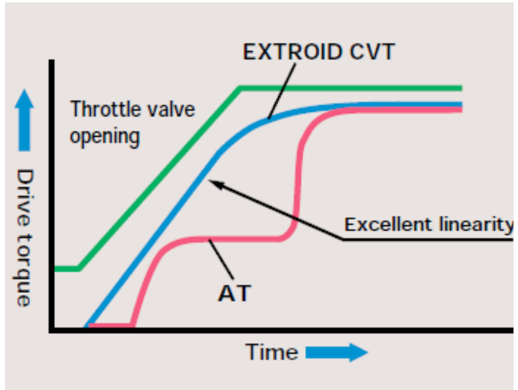
Because the ratio change occurs seamlessly while power is being transferred there is no interruption of power to the wheels as there is in most other forms of transmission.

The servo piston is connected to a shuttling spool valve that can direct high pressure oil to the front or back of the piston causing the pistons to move.

When the piston moves and the roller rotates a rotating cam communicates this movement to a system of levers that are restrained at one end by a stepper motor. The stepper motors position can confirm the position of the roller. When the roller is in the correct place the stepper motor is used to move the spool valve back so that the servo piston repositions the roller in the centre position.

Although this method appears quite simple it is an indirect method of changing ratio and requires a complicated subsystem of stepper motors, cams, and hydraulics to ensure stability. The basis of this control system is outlined in the diagram below again explaining the Extroid Transmission.

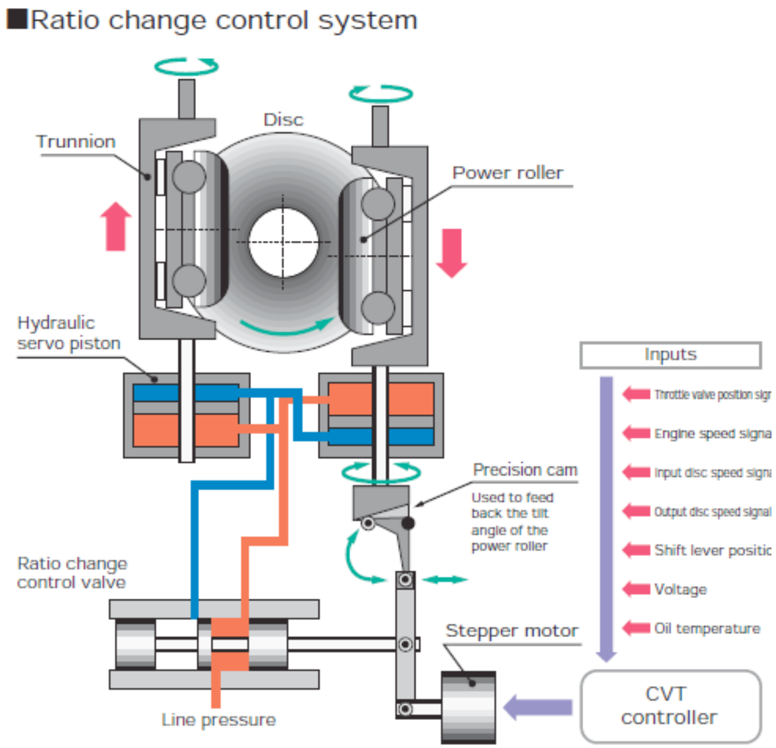
Since the discs are rotating at high speed, the rollers can tilted the necessary amount by moving them up or down o slightly (around 0.1mm - 1.0mm). This enables the EXTRC CVT to respond instantly to a ratio change command a results in exceptionally quick ratio changes.



Ratio Control of SHTV

The steps associated with a NSK type variator ratio change are as follows:

1. A driver or environmental change occurs that is interpreted by the control system as one that requires a ratio change.
2. The control system selects the ratio that is required.
3. The control system uses look up tables to select a new position for the stepper motor that will coincide with this ratio.
4. The stepper motor moves to the new position and opens a spool valve connected to the piston to apply pressure to one side or the other of the control piston.
5. The trunnion rotates and a precessing cam, that bears up against a lever connected to the stepper motor reverses the action opening the spool valve to the other side so that the spool valve moves back and causes the servo pistons to move to the central position.
6. The process repeats until such time that the correct ratio is achieved and stabilized.



The action can be described as a “nudging” action in which the rollers are nudged into a new position. They are not simply moved there as in a gear change in a “normal” automatic transmission.

Ratio Control of SHTV

The result is a somewhat unstable continually in flux roller positioning. The rollers are not connected and each one is free to adopt slightly different positions. Within the toroidal cavity. It is also a very expensive arrangement as each roller is controlled independently.

Because of the inherent instability the roller trunnions are connected with a somewhat "loose" system of pulleys and cables. This agricultural solution to an otherwise quite sophisticated arrangement is testament to the instability of the system.

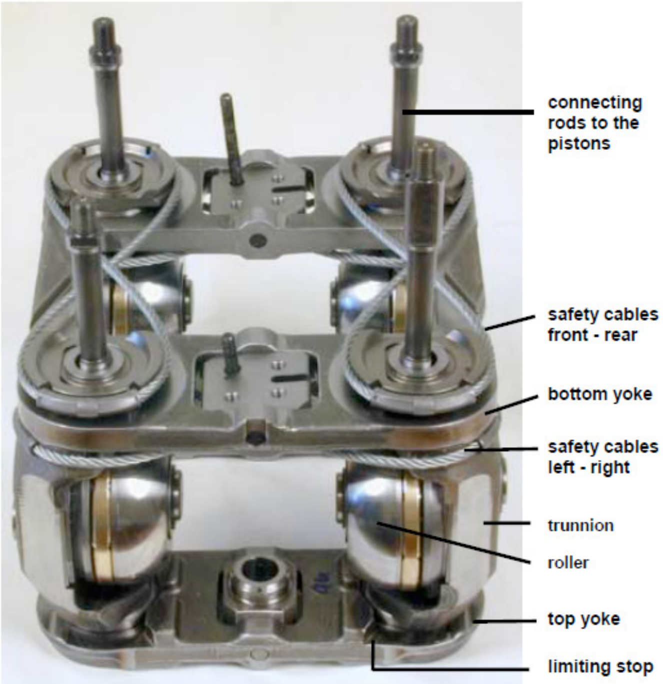
It is important to understand that this system is always subject to a ratio over-run.

If we take a ratio control command that produces the movement shown in step 1 2 & 3 in the diagrams above, it can be seen that by pushing the roller forwards the input point moves outward towards a "high" gear. In this position the reaction force on the roller becomes less.

As the reaction force becomes less the hydraulic pressure in the servo pistons will accelerate its movement causing a very rapid runaway situation that must be controlled very quickly and precisely so that an overreaction does not happen. In addition to this phenomenon as the roller moves off line in the toroidal cavity the "squeezing action" of the two discs adds an additional force on the roller in the direction of the first movement step. This means that less force is required as soon as the roller moves off line.

The control system requires a continual balance to maintain any specific ratio and when ratio changes occur, the control system must respond extremely fast and accurately to prevent overrun and associated correcting vibrations.

The control of a SFTV roller is similar and is subject to the same instabilities.



The photograph below is of a typical 4 roller Extroid arrangement with associated comment by Professor P.Tenberge and J. Mokel entitled "Toroidal CVT with compact Roller Suspension"

The control of a DFTV is much more direct. It does not require any closed loop feed-back to execute a ratio change and so does not encounter these problems.

Ratio Control of SFTV

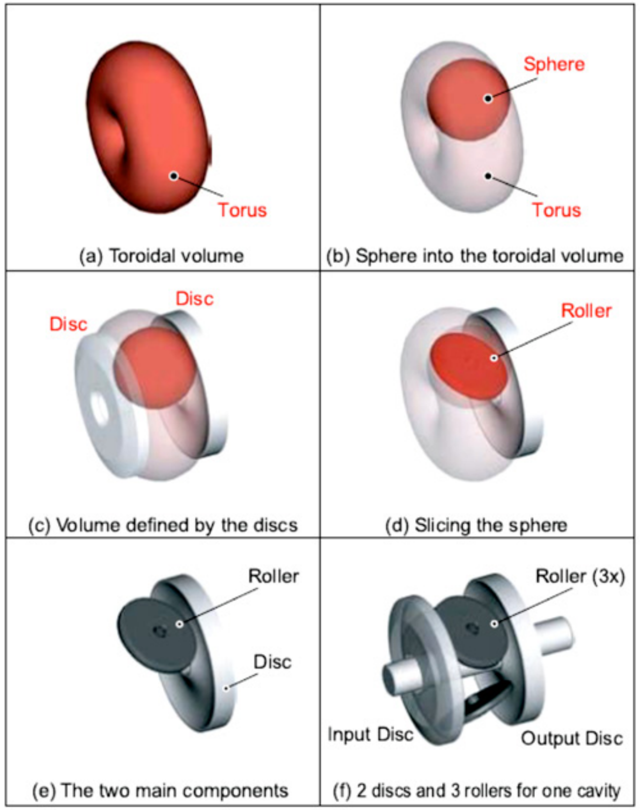
The Single Roller Full Toroidal Variator (SFTV) is controlled using a steering method that allows very rapid ratio change, coupled with a mechanical linkage that confirms the positions of the rollers within the toroidal cavity, and registers the torque being transferred.

This unique arrangement allows for a continuous feedback of the torque being transmitted by the system which can be applied to the clamping system so that the clamping force always relates to the torque transfer. Torotrak call this method of control “Torque Control” as distinct to “Ratio Control”.

The Torotrak SFTV is controlled in a similar manner to the SHTV but avoids the overrun instability associated with the NSK solution.

The Full Toroidal arrangement leaves the rollers with no side thrusts and so there is no need to be mounted in ridged trunnions designed to transfer the side thrust back to the body.

The diagram below outlines how the rollers are arranged within the Full Toroidal cavity.



These diagrams are taken from a joint paper by Torotrak and Jtekt on the subject of torque control

Ratio Control of SFTV

The discs are subjected to an end load provided by a hydraulic piston. This end load clamps the discs onto the rollers with a force that can be varied dependant on how much torque is being passed through the variator

When transferring power the rollers are subjected to two reaction forces that act in the same direction, where torque is provided into the rollers by the input disc and where torque is transferred out of the rollers into the output disc.

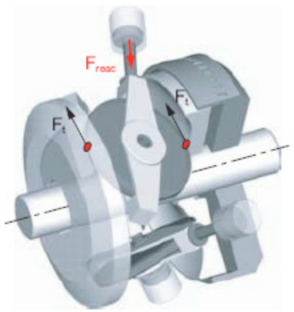
The rollers are supported on hydraulic pistons similar to the pistons in an NSK SHTV but have no trunnion and are free to move freely within the cavity. These pistons support the torque reaction forces.

The pistons are rigidly mounted and connected to the Roller yoke by a ball joint. This is not shown in these diagrams.

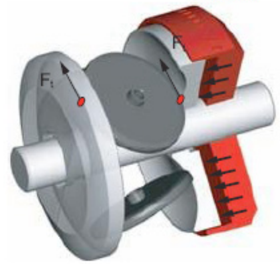
The pistons and the connection system to the rollers is arranged slightly out of plane with the rotational plane of the discs. The angle formed is called the Castor Angle and is responsible for a degree of stability that is somewhat better than that of an NSK SHTV

The pistons are supplied with high pressure oil at a pressure controlled by a control system.

The pressure supplied by the control system is responsible for the position adopted by the rollers within the cavity. The rollers will move one way when under the influence of a pressure that creates a force that is higher than the torque reaction coming off the rollers and the other way if the force is less than that.



(b) Reaction force



(a) Endload or clamping force

These diagrams are taken from a joint paper by Torotrak and Jtekt on the subject of torque control

Ratio Control of SFTV

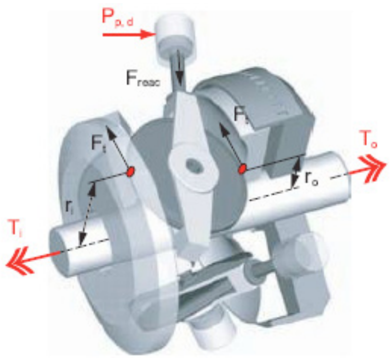
Typically when the rollers are in the centre position or 1:1 ratio, the rotational axis of the rollers pass through the rotational axis of the discs. In this state the rollers remain in a stable equilibrium position, provided the pressure to the servo pistons creates a force that balances the Torque Reaction Force off the roller.

If the force is not balanced the rollers will move "forward" or "backward" within the cavity. When they do this their rotational centre no longer passes through the rotational centre of the discs and they are subject to a rotating couple.

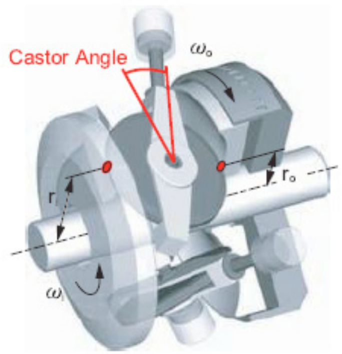
Because the servo pistons are angled at the castor angle as they move the roller forward or backward it will rotate under the influence of the dynamic forces off the discs. However it will also rotate because of the "cam" like action of the toroidal cavity itself. The piston is rigidly mounted so as the ball connection to the roller yoke moves in and out the ball moves up and down under the influence of the castor angle. In order for the yoke to track the ball connection it must change ratio.

The roller rotates and turns within the cavity so that its ball joint connection to the servo piston remains in the correct place as it moves upward or downward under the influence of the castor angle.

Torotrak simply call this Ratio Tracking which over simplifies a very complicated geometrical interaction.



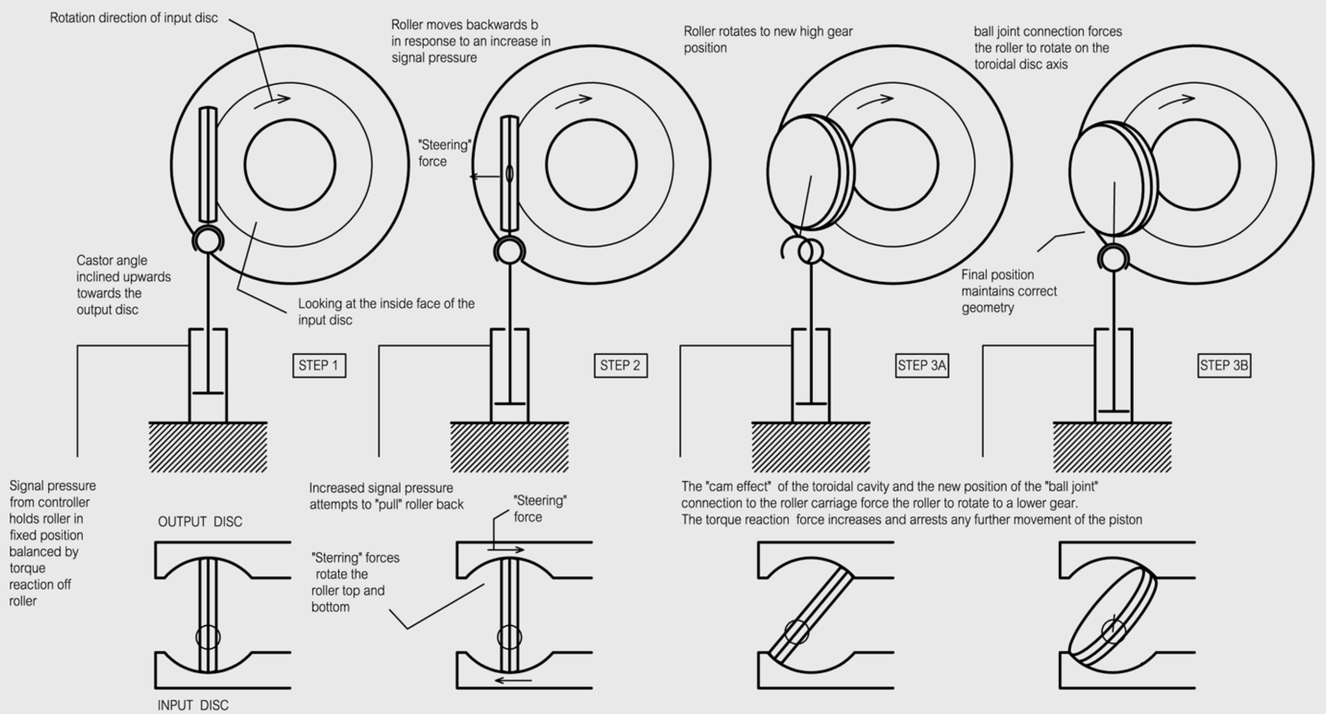
(c) Torque control



(d) Ratio tracking

These diagrams are taken from a joint paper by Torotrak and Jtekt on the subject of torque control

Ratio Control of SFTV



VARIATOR IN "NORMAL ACCELLERATION " MODE MOVING TO A HIGH GEAR POSITION.

Diagram 1A (above) shows how this simultaneous rotation and repositioning of the Servo Piston ball joint occurs.

It can be seen that as the roller moves forward the reaction vector force from the input disc, moves the contact inward while the output contact is moved outward. The CVT is moving to a lower gear.

When the roller rotates it is forced because of its connection via a ball joint to the rigidly mounted servo piston, also to reinstate its centre of rotation in line with the centre of rotation of the discs and the rotating action ceases.

In this case the roller adopts a new ratio and is subject to a new torque reaction force which is balanced by the control pressure from the control system.

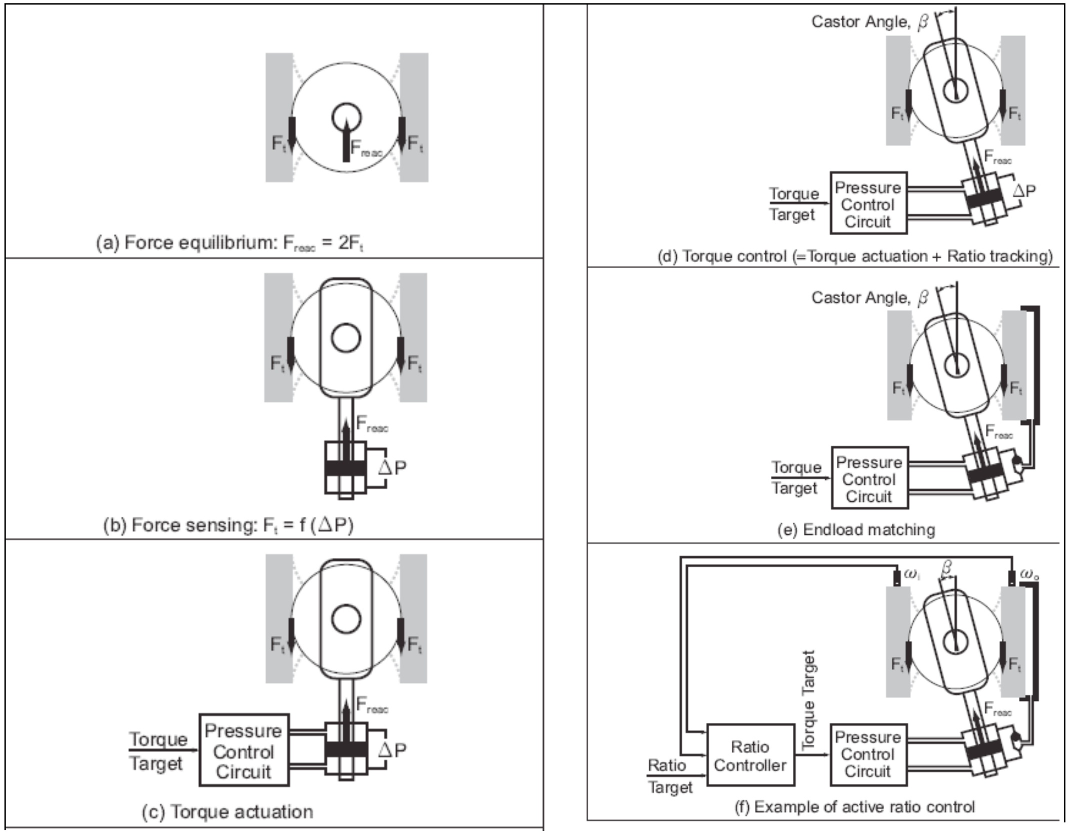
This type of indirect control is aptly described in the diagrams below. The control system provides a torque target that indirectly targets a ratio target.

The notion of target is just that. A target being something that can never be struck in exactly the right place.

Ratio Control of SFTV

The control system requires a continual balance to maintain any specific ratio and when ratio changes occur, the control system must respond extremely fast and accurately to prevent overrun and associated correcting vibrations.

Like the SHTV control, a continuous closed loop feedback is needed to achieve any degree of stability.



(a) Force equilibrium: $F_{reac} = 2F_t$
(b) Force sensing: $F_t = f(\Delta P)$
(c) Torque actuation
(d) Torque control (=Torque actuation + Ratio tracking)
(e) Endload matching
(f) Example of active ratio control

These diagrams are taken from a joint paper by Torotrak and Jtekt on the subject of torque control

In late 2000 Toyota pulled out of a deal with Torotrak because of this issue.

Japan Toyota Motor Corporation has decided to cease development of the IVT and to terminate its licence agreement with Torotrak.

Toyota gave the reason as `unacceptable driveability' in the form of a vibration in the Toyota IVT equipped vehicle. Toyota chose to conduct the design and development of their own transmission and vehicle without accepting solutions or hands-on involvement from Torotrak.

"We are disappointed with their decision, having demonstrated to Toyota in Japan in August 2000 the excellent vibration free driveability of a sport utility vehicle equipped with a Torotrak designed Series 3 IVT," said Maurice Martin, chief executive of Torotrak …

Ratio Control of SFTV

*In order to understand this instability better go back to **Diagram 1A.***

- When a lower ratio is "targeted" the rollers must rotate so that the input point moves closer to the central axis. In this position the Torque Reaction Force will increase.
- This happens if the roller moves forward in the cavity when arranged as in Diagram 1A above. If it moves back the reverse happens.
- To move forward the pressure signal from the controller must reduce.
- As soon as it is reduced it must immediately reestablish itself at a higher pressure or the system will run away. There is no signal to establish exactly where the rollers are.
- This is a knife edge control subject to oscillations that are very difficult to dampen out.

The control of a DFTV is much more direct and does not encounter these problems. The ratio control signal is just that, one signal that remains in place during and after any ratio change. It is not a target but a specific request.

Ultimate Transmissions maintain that the particular control method adopted by Torotrak is too unstable for incorporation in an IVT with geared neutral. The Torque Reaction Force fluctuations being experienced by the rollers when approaching "geared neutral" make this sort of control too sensitive to external environmental changes. It is quite simply an unsafe control system.

However this instability the Torotrak system has one big advantage and that is that the Torque Reaction Force which is a measure of the tangential forces being experienced by the contact points, can be used to control the clamping force. Modulating the clamping force in line with fluctuations in the Torque Reaction Force (TRF) can ensure that the CVT is not over or under clamped.

Not with standing this "advantage" it can be seen that in order to initiate a ratio change it is necessary (at times) to lower the pressure provided to the roller before the roller moves to a new ratio. Under some circumstances this lowering of pressure will unclamp the roller sufficiently for gross slip to occur, particularly when the variator is being operated using a high traction coefficient or at high temperatures.

This is subject to a more detailed explanation in "Clamping" included in the pdf on Understanding DFTV design .

Ratio Control of DFTV

Ultimate Transmissions have developed a modified roller control method that can be applied to both a DFTV and a SFTV. It is called Direct Roller Steering or DRS.

DRS avoids the instability associated with both the SFTV and SHTV control methods adopted by Torotrak or NSK.

It can be arranged to respond to Torque Control or Ratio Control commands.

The rollers in a typical SFTV are mounted in a Yoke that is connected to a trunnion using a ball joint.

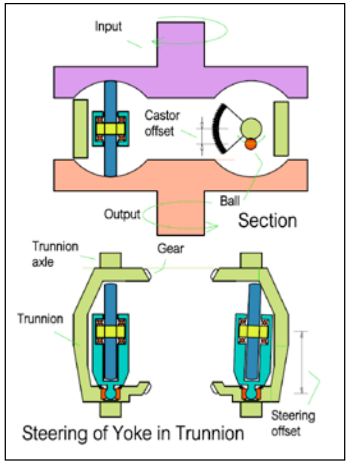
The trunnion is supported on axles that are held in the rigid body surrounding the CVT.

The ball joint connection is located off centre to the roller rotational axis by a distance (castor offset) that provides a similar geometrical affect to the Torotrak Castor angle.

A gear rack type actuator engages with a simple spur gear on the back of one of the trunnions so that as it moves up and down the trunnion rotates.

Each trunnion is geared to the others so that when one moves they all move.

When an attempt is made to rotate the trunnions the ball joint translates slightly within the cavity because of the castor offset and the roller is “steered” slightly an amount proportional to the size of the steering offset.



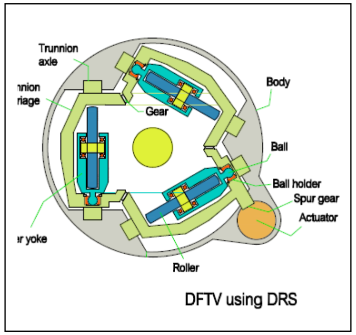
Steering of Yoke in Trunnion

The contact points on the rollers restrain the roller from sliding over the surface of the disc because of the high clamping force and contact friction coefficient.

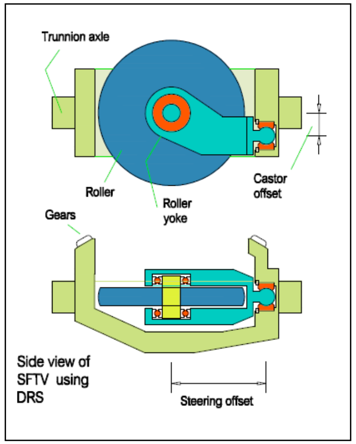
The sideways (translation) movement of the ball joint caused by the castor offset turns the roller. The input contact moves in one direction and the output in another. It is exactly the same mechanism that moves the rollers in a SFTV and a SHTV.

As the roller steers to a new ratio the yoke realigns itself with the centre of the trunnion and the movement ceases.

It is somewhat easier to understand DRS applied to a SFTV so this is explained first



DFTV using DRS



Side view of SFTV using DRS

Ratio Control of DFTV

Ultimate Transmissions have also developed a method of registering the Torque Reaction Forces that are being exerted on the rollers. **This is called TRFR or Torque Reaction Force Registration.**

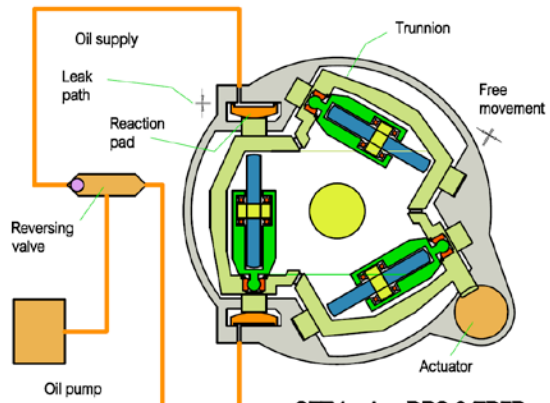
This method is similar to that used by NSK and Torotrak but operates independently of the ratio control of the rollers and so can be incorporated in the overall design or replaced with another electronic method as is done with the NSK design.

TRFR involves supporting the trunnions on a reaction pad that is connected to a high pressure oil supply as shown below.

A very small hydraulic pump supplies oil via a reversing valve (that allows for positive and negative torque reactions) to the underside of two reaction pads.

The reversing valve supplies oil to only the closed pad that is supporting the reaction force. The oil pressure builds up until the pad starts to leak at which point the force under the pad equals the Torque Reaction Force and so the pressure in the supply line is directly proportional to the reaction forces that are being experienced by the contact points, and can be used to supply the clamping system.

The movement of the reaction pads is very small provided the supply pump is small. This movement causes the roller to move slightly off line and adopt a ratio that is slightly different from the other rollers. If a similar clearance is provided for the other (drone) trunnions this effect is minimized by ensuring that the movement of the trunnion is kept at a minimum. If all trunnions are fitted with reaction pads although the parts count will increase the relative movement will be the same.



SFTV using DRS & TRFR

Ratio Control of DFTV

TRFR can be used to create a torque controlled ratio change in the variator so as to mimic the Torotrak method, or the ratio control can be direct with the TRFR only being used to control the clamping force and supply information on the torque being transferred.

A double acting piston is arranged with a rack gear to interact with a spur gear on one of the trunnions.

A control pressure is fed to one end of the double acting piston and the other end is fed with the pressure signal from the TRFR system.

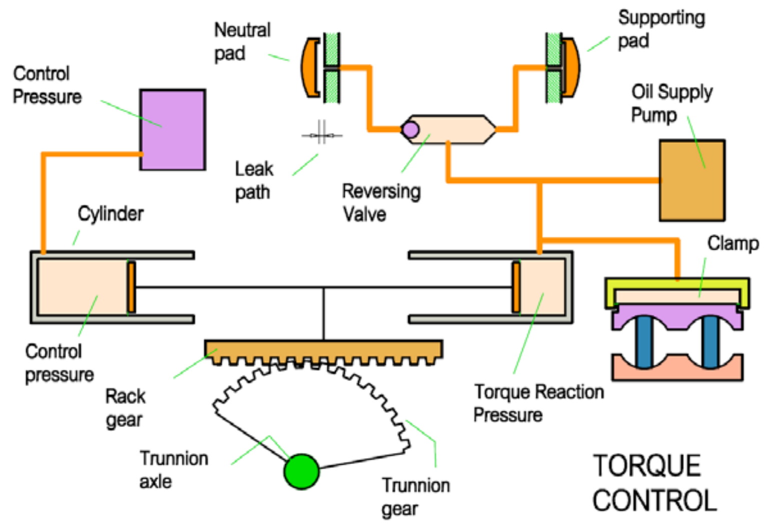
If the pressure in the TRFR end is less than that of the control pressure then the pistons will move to the left rotating the trunnion to a lower gear where the torque reaction force will become greater and the movement will stop.

Conversely if the Torque reaction pressure is less the movement will be towards a higher gear.

Once a Control pressure is selected the ratio change occurs without any need for further closed loop feedback as with a Torotrak or NSK control.

Although this type of Torque controlled ratio change is favored by Torotrak and they take great pains to distinguish it from Ratio control the use of this type of roller control allows a choice to be made.

Ultimate Transmission's study indicates that a simple electronic control using a stepper motor will be far more useful, cheaper and more stable than torque control and recommend it ahead of torque control.



The diagram (above) shows a simplified control system how TRFR can be used to create a torque controlled ratio change.

Ratio Control of DFTV

The force required to change ratio is very small as the rollers are steered into position not forced as the case with Torotrak.

The **TRFR** pressure is only needed to control the clamping pressure if simple ratio control is being used.

With an electronic ratio control the hydraulic supply for the clamp can also be provided using an electric motor because it is now very small having nothing to do with the rate of ratio control simply needed to provide make up oil for leaking of the clamp system. The electric motor driven system can also provide oil for lubrication and cooling via a low pressure high volume pump.

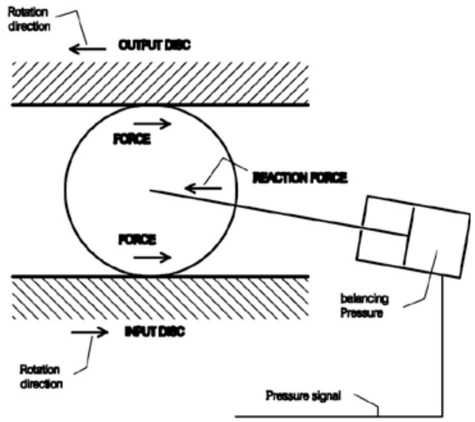
When an electric motor is used to provide all of the hydraulics there is no interruption of oil supply when the IC engine is turned off. This is particularly useful for a traction CVT as it will never need to start up without oil. It is essential if automatic “stop start” fuel saving and CO2 reduction systems are to be applied to a vehicle.

The energy losses associated with the hydraulics needed for a SFTV using Torque Control are around 5.0% while those of a Variator controlled using DRS and TRFR are more like 1.0%.

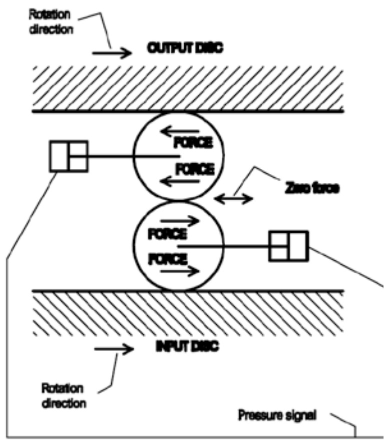
This method of control can also be applied to a DFTV with equal effect. It must be understood however that each roller must be controlled separately because they are subjected to Torque Reaction Forces that are in different Directions, and both the input.

The Rollers in a DFTV can not be supported on moving pistons they must be supported on reaction pads as shown to the right, if a torque reaction Force is being measured. and output discs rotate in the same direction .

The Diagram below shows the fundamental difference in reaction forces in a DFTV and a SFTV or a SHTV.

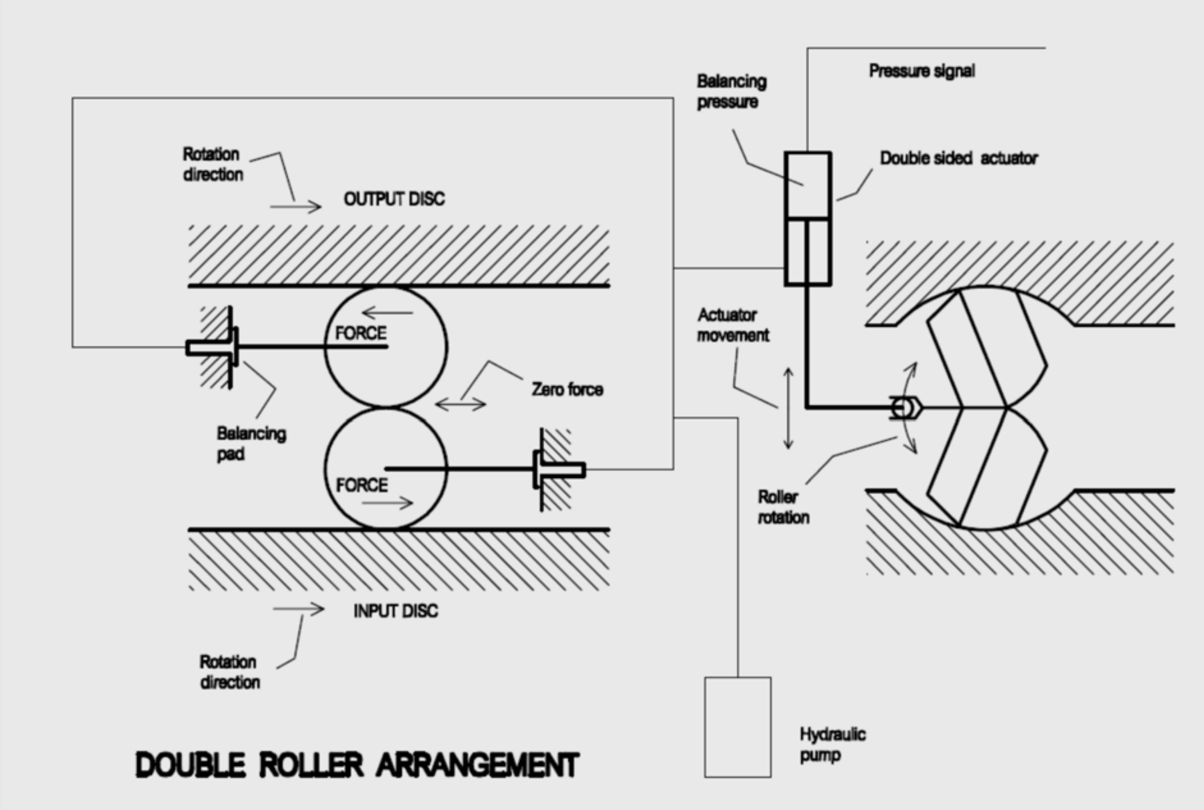


SINGLE ROLLER ARRANGEMENT



DOUBLE ROLLER ARRANGEMENT

Ratio Control of DFTV



These pads can be used to provide the **TRFR** system as described for the **SFTV.**

If the Torque Reaction Force is not required to be measured then they can be rigidly supported on trunnions.

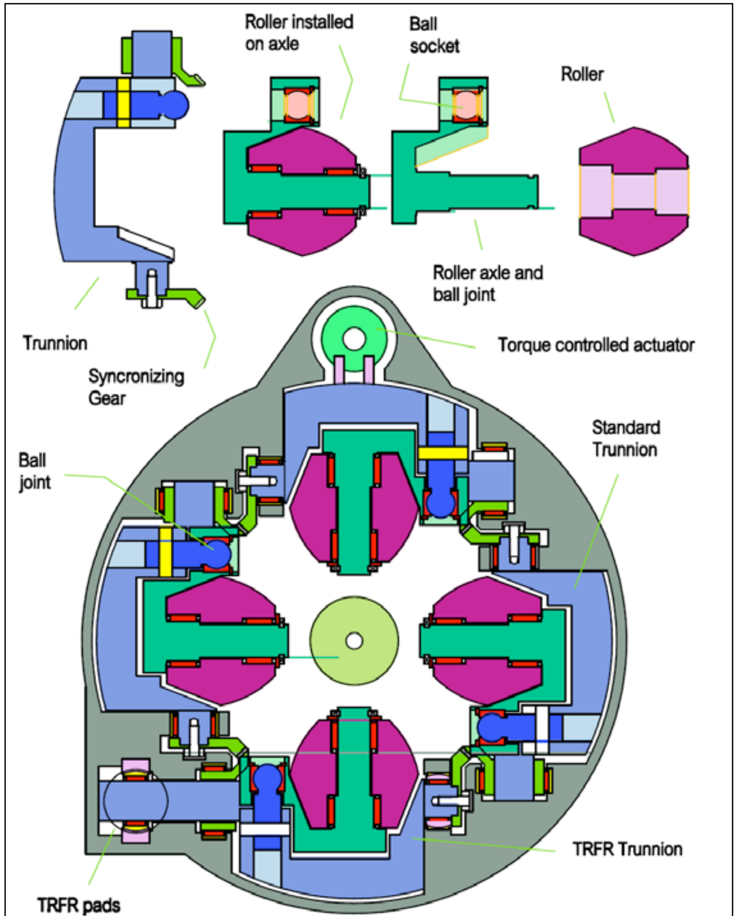
In reality torque reaction pads must be provided on both sides with a reversing valve to allow for acceleration and deceleration events.

Ratio Control of DFTV

Detailed DFTV Control System using External Steering Offset

There are a number of DRS options available for the support of the rollers in a DFTV

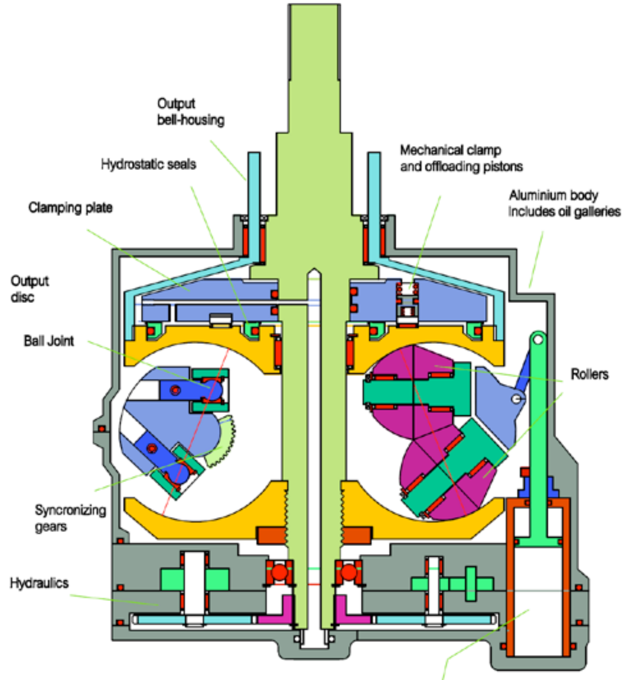
The first of these is similar to that employed by the SFTV mounting using a yoke with a ball joint connected to a common trunnion.



SCHEMATIC OF DFTV MODULE USING DRS & TRFR (With torque Control)

Left is a plan view of a 4 roller arrangement using a ball connection and an active trunnion that is used to register the torque reaction.

The section below shows where the ball joints are located supporting the roller pair.



SCHEMATIC OF DFTV MODULE USING DRS & TRFR (With torque Control)

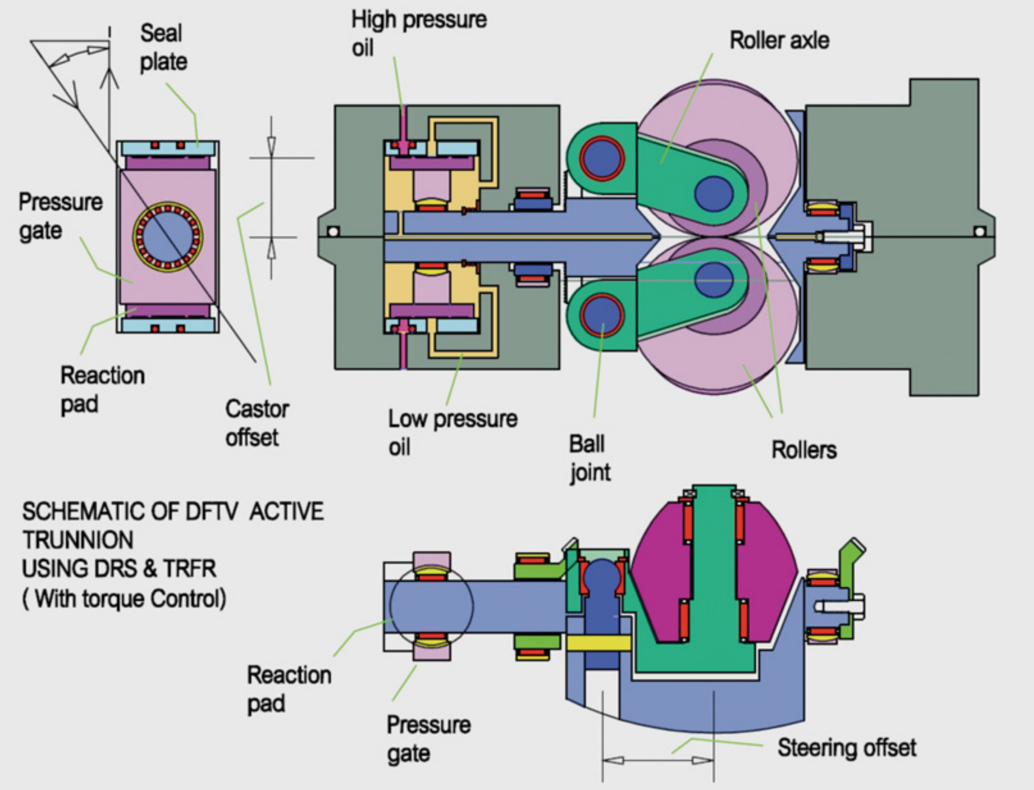
Ratio Control of DFTV

The active trunnion is arranged to provide a hydraulic pressure that is proportional to the torque reactions off the rollers as shown in this section.

When the trunnion is rotated while the CVT is in motion, the balls moves to one side and the other of the centre causing the rollers to steer in one direction for the input and the other direction for the output. Because both discs rotate in the same direction the alternate contacts must “steer” in different directions, similar to the ratio adjustment that occurs in a SFTV using DRS.

The roller pair now steers to a new ratio, and the pair stabilize.

The amount of steering is of the order of 1 degree. This means that the conical contacts become slightly misaligned. The contact changes from being a lozenge shape (approximately rectangular) to approaching a long ellipse with truncated ends. The length of the contact in the rolling direction is much wider than the misalignment caused by the 1 degree movement.



With a DFTV the castor offset is automatically provided because there are two rollers with their rotational centres already located above and below the centre line of the toroidal cavity.

The Steering Offset is as for the SFTV being the distance from the centre of rotation of the roller to the centre of the ball.

Ratio Control of DFTV

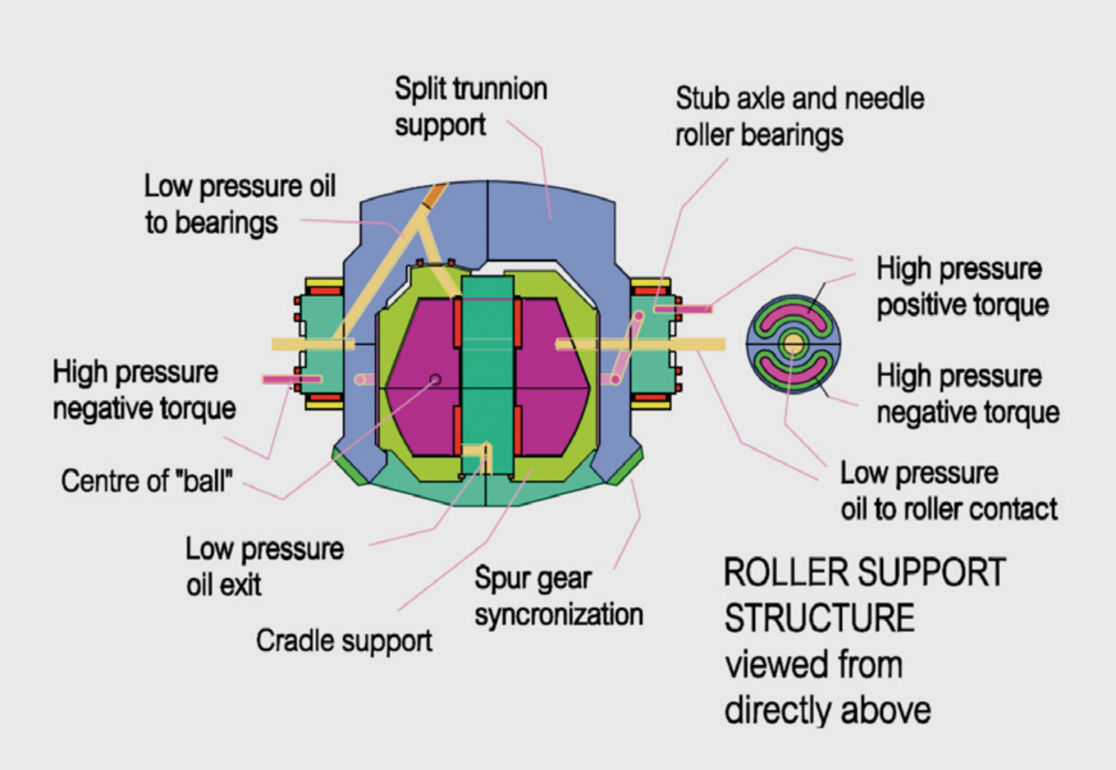
Detailed DFTV Control System Using Internal Steering Offset

A second roller support option, capable of DRS and TRFR is shown above. The "ball" is now internalized with its centre inside the ball itself. The "ball" is shown green in the diagram above captured by the ball socket (dark blue) which is now the split trunnion.

Each end of the "ball" is supported on a hydrostatic pocket one that is acting when under acceleration and one acting when under deceleration.

The trunnion is supported on axles as before. These axles communicate with oil galleries in the CVT body that deliver

1. Low pressure oil for cooling and lubrication to the roller contacts and to the needle rollers that support the rollers.
2. High pressure oil to the hydrostatic bearings that support the ball during acceleration or positive power.
3. High pressure oil to the hydrostatic bearings that support the ball during deceleration or negative power



These oil supplies enter at both ends of each trunnion.

A small clearance is maintained between the "ball" and the socket so that sufficient leakage can occur to register the Torque Reaction Forces properly.

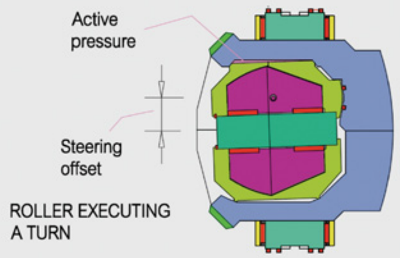
Only a very small section of ball and socket is formed as the ball never moves more than 2 degrees.

The "ball" itself supports the roller axles.

Ratio Control of DFTV

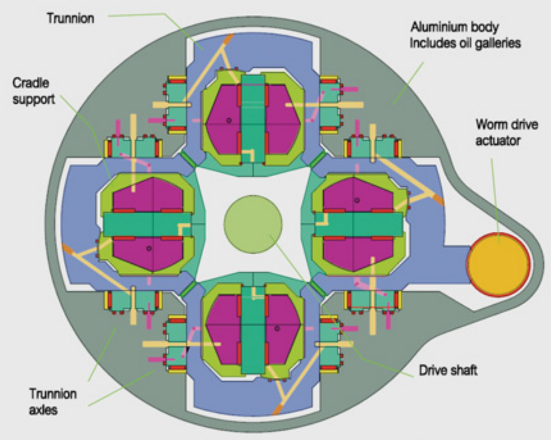
When the trunnion rotates the roller steers as before, forcing the ball to move within the socket. The hydrostatic support reduces the friction to almost zero for this movement so that although the steering offset is small compared to the design using the externally mounted ball the steering movement requires very little force. The castor offset is as before.

In a typical 430 Nm. DFTV design (ratio spread 5.5) with a toroidal cavity radius of 40.96mm. rotating at 1,000RPM a 1 degree “steer” will execute a full sweep in around 0.5 seconds.



ROLLER EXECUTING
A TURN

When four rollers are arranged as before the layout becomes:

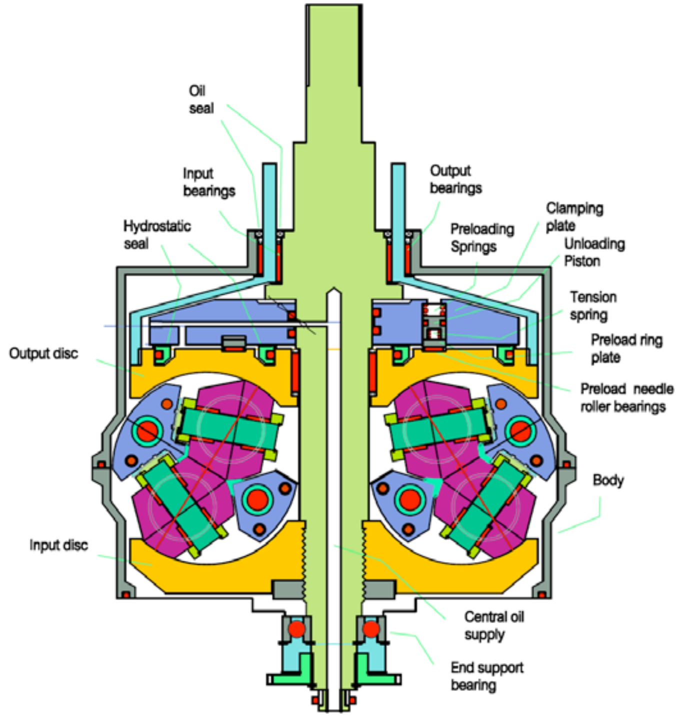


SCHEMATIC OF DFTV MODULE USING
DRS & TRFR

The ratio control can be arranged as a torque control system as detailed earlier or as a direct ratio control using a stepper motor and worm drive as shown here.

A section through this arrangement is shown to the bottom left.

The clamping system is connected directly to the high pressure oil under the ball carriage support bearings.



SCHEMATIC OF DFTV MODULE USING
DRS & TRFR

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