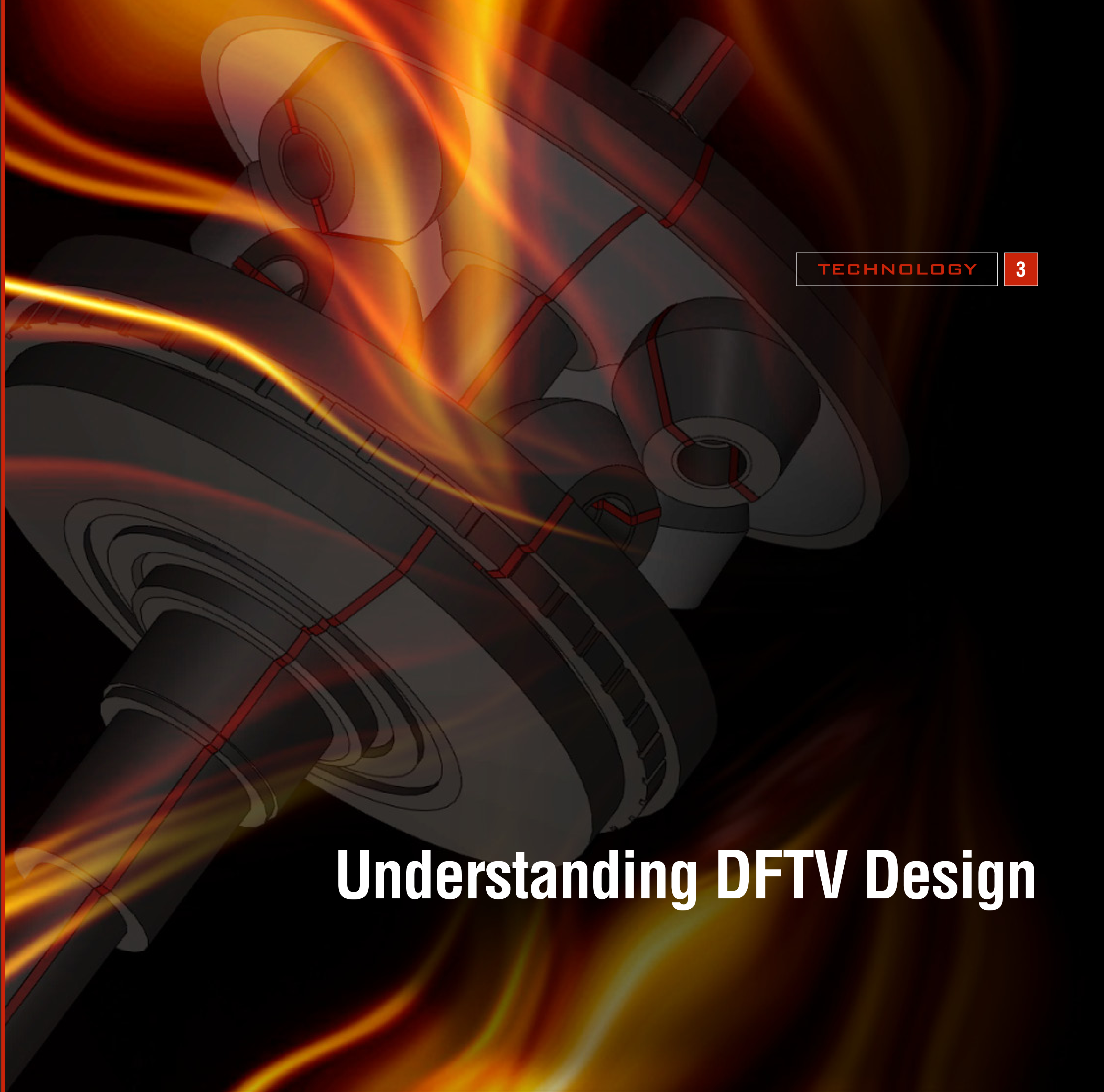
UTIMATE TRANSMISSIONS

TECHNOLOGY 3



Understanding DFTV Design

UTIMATE TRANSMISSIONS

Contents

Overview

Toroidal variators and traction drives in general are well understood and can be designed with a similar level of confidence to that required when designing geared devices.

While the correct amount of force is applied to the roller and disc contacts torque can be transferred form roller to disc and vice versa without slippage and without damaging the metal parts as if it were a toothed gear, provided certain fundamentals are followed.

The three most important being;

1. The maximum Hertzian Pressure that the metal parts can sustain before they become permanently deformed.
2. The traction coefficient characteristics of the traction fluid being used, over the temperature expected at the contact points.
3. The duty cycle expected of the transmission so that adequate life can be maintained.

The maximum hertzian pressure is a limit that is also placed on other forms of rolling element bearings. Some allowance must be made because typical DFTV designs include more than three roller pairs which will give rise to some degree of uneven load distribution dependant on manufacturing tolerances and the flexibility of components. The maximum contact stress limit is generally taken as 4.2GPa. Ultimate transmissions designs a maximum of 3.95GPa

The traction coefficient can be determined by a careful study of published information with a working prototype trials to confirm that the selection was correct. Although a sensible safety margin should be maintained if the temperature effects and fluid characteristics are well documented by the manufacturer. The maximum traction coefficient for a typical fluid is maintained by Ultimate Transmissions as 0.05.

The maximum stress cycle limits are 380 million at mean contact stress of 2.1GPa.

Clamping

The discs in any toroidal variator must clamp over the rollers with enough force to ensure the Torque Reaction Forces (TRF) are transferred from the input disc to the roller and from the roller to the output disc. Notwithstanding the need for high clamping forces they cannot be greater than the strength and endurance of the roller and disc material capabilities

All three types of variators are controlled by exactly the same physics in this regard.

The maximum TRF will always equal the clamping force x the maximum design traction (friction) coefficient. *Ultimate Transmissions uses a maximum of 0.05 for its current designs, in line with NSK limits for the SHTV, when "spin" velocities of around 1.8m/sec are present and contact temperatures are less than 140 deg C.*

The maximum Clamping force is limited by the physical limits of the material. *Ultimate Transmissions uses 3.95GPa as the limit for its current designs in line with NSK limits for the SHTV.*

The maximum number of stress cycles that the materials can deliver. *Ultimate Transmissions use a limit of 380 million cycles at a mean contact stress of 2.1GPa (3.15GPa maximum)*

There are a number of different ways to arrange the clamping action.

Ball Ramp

The first is the simplest in which a ball ramp is built in between the input and output rollers. This ramp is designed to produce a clamping force that is proportional to the input torque. This method was first used in the early NSK SHTV, and is used by Torotrak in simple applications and CVTcorp.

The drawback with this method is that the input torque is unaffected by the roller position and the roller position affects the actual TRF. When the roller is in low gear position the TRF is much higher (nore than double what it is when in high gear with the same input torque.

The roller ramp must be arranged to provide sufficient clamping force at low gear so no gross slipping can occur so that in high gear the roller is over-clamped by over 100%.

Clamping

This is a useful way of clamping for simple mechanisms but is not always suitable for high power or high efficiency CVT's with high endurance. The use of a simple ball ramp clamped CVT operating in an automotive application will reduce the life by around 20% or require an increase in physical size of around 5% to achieve the same life expectancy of the rollers and discs.

Torque Reaction Force Registration (TRFR) using Hydraulic Reaction Pads

At the surface of the discs where the rollers make contact a tangential force is transferred. This force is called the Torque Reaction Force or TRF. It is the real force being transferred, not just the input torque related to a fixed lever arm, as the case for a ball ramp.

In a Torotrak SFTV this force is supported on pistons so that there is always an accurate register of it in the form of a hydraulic pressure.

In a DFTV using TRFR there is also an accurate register of this force in the form of a hydraulic pressure. The registration of this force in a SHTV is not so direct.

This hydraulic pressure can be used to directly drive the clamping force, using a very simple formula

$A = a/\mu \times N$ where
A is the area of the clamping piston
a is the area of one control piston
μ is the design traction coefficient
N is the number of rollers in one cavity

There are however some secondary considerations

The Reaction Force between the roller and disc is equal to the Clamping Force / COS of the angle of inclination of the roller within the toroidal cavity. It is not equal to the Clamping Force itself. As the roller moves within the cavity it is subject to a wedging effect and with a constant clamping force the actual reactions increase. Only in the centre position is it "equal" to the clamping force.

The value of μ reduces under the influence of increasing temperature and under the influence of increasing "spin" or differential velocity at the contact points.

Clamping

In a typical SFTV using TRFR from the control pistons the value of μ remains relatively constant while operating at the same temperature. This means that it must be set for the centre or 1:1 position where typical "spin" velocities are over 2.4m/sec. This results in moderate over-clamping at other ratios because of the wedging effect. The spin velocities in a (430Nm.) SFTV operating at 6,000 RPM are as follows.

Single Roller Full Toroidal Variator Differential Velocities (at 6,000 RPM) and Reaction Forces.

Ratio	Input Spin Velocity	Output Spin Velocity	Increase In Reaction Force	Actual Traction Coefficient	Actual Contact Stress Limits
	m/sec	m/sec	m/sec		GPa
0.426	1.41	0.53	12%	0.044	3.95
1	1.22	1.22	0%	0.05	3.48
2.342	0.93	2.47	12%	0.044	3.95

It can be seen that the over clamping may have a beneficial effect in high gear where spin velocities are the greatest but in low gear it is simply over-clamped.

A similar chart for the DFTV shows that the extra clamping coincides with the areas of highest spin.

Double Roller Full Toroidal Variator Differential Velocities (at 6,000 RPM) and Reaction Forces.

Ratio	Input Spin Velocity	Output Spin Velocity	Increase In Reaction Force	Actual Traction Coefficient	Actual Contact Stress Limits
	m/sec	m/sec	m/sec		GPa
0.426	1.02	0.92	12%	0.044	3.95
1	0.0	0.0	0%	0.05	3.48
2.342	1.61	1.79	12%	0.044	3.95

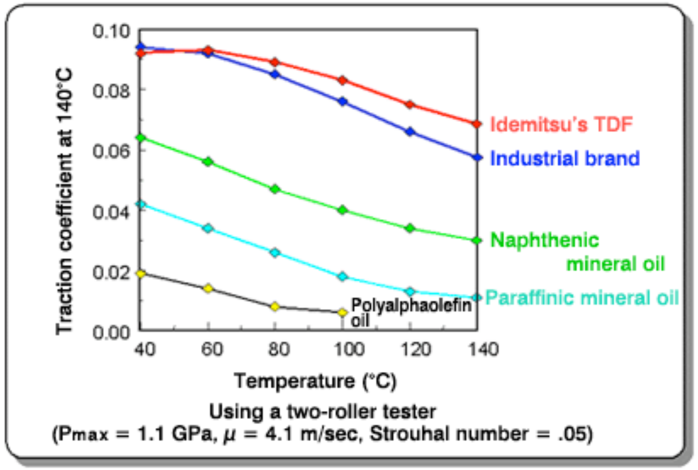
It must be noted that if a DFTV control system using an active trunnion for TRFR it automatically cancels out the extra clamping.

Torque Reaction Force Registration (TRFR) Using Load-Cells

A load-cell can be used to replace the torque reaction pads with the signal converted back to a hydraulic pressure. The load-cells generally have a smaller movement when registering the force which has advantage for a system using a single active trunnion.

When the signal is in electronic form it becomes much easier to make adjustments associated with increasing the clamping force as the temperature of the traction fluid increases.

It is well understood that as the temperature of the traction fluid increases the traction coefficient decreases.

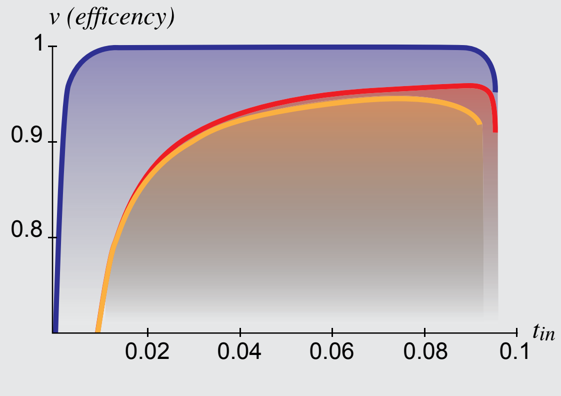


The chart above maps Idemitsu's traction fluid that was developed for NSK. It is clear that significant reductions in clamping pressure can be applied while the fluid is at a modestly elevated temperature.

Use of a clamping control system that compensates for temperature can extend variator life considerably, decrease the variator size or improve its efficiency.

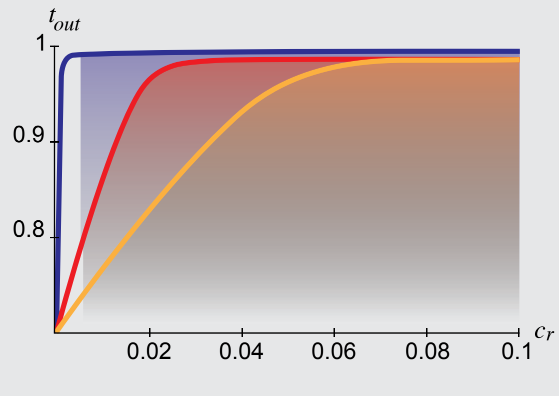
It is understood that in the recent versions of the NSK SHTV the clamping pressure is built up electronically so that the variator rollers are always optimally clamped.

Clamping



The efficiency vs. the input traction, for the three toroid geometrics.

Calculations are done at a ratio S_{rID}=1 and clamping force F_D = 22kN



The output creep vs. the overall creep for for the three toroid geometrics.

Calculations are done at a ratio S_{rID}=1 and clamping force F_D = 22kN

The chart above identifies the efficiencies and creep of a DFTV and a SFTV or SHTV of the contact and support bearings only. This chart is taken at a 1:1 ratio.

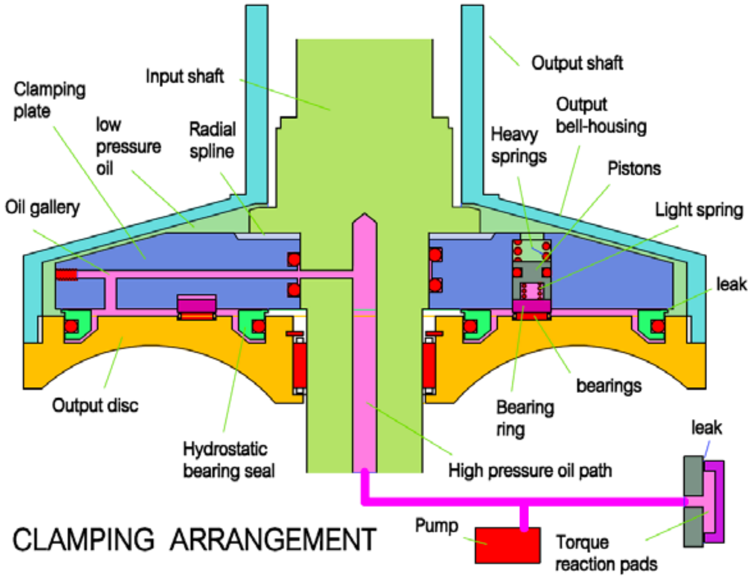
It can be seen that increasing the traction coefficient for both the SFTV and the SHTV improves its efficiency markedly. In the case of the SHTV this is because of the thrust bearings that become more and more loaded as the traction coefficient is decreased and the clamping is increased. In the case of the SFTV the loss of efficiency is caused by the enlarging contact patch as the coefficient is decreased.

In the case of the DFTV varying the traction coefficient does not have as much effect on the efficiency. It will only decrease the power density, or reduce the variator life. At other ratios there is a greater affect on efficiency but it is never as pronounced as for the other two.

Clamping

Hydraulic Clamping Method

Ultimate Transmissions have developed a combined Hydrostatic bearing and clamping system that enables a single cavity to be used which simplifies the mechanical design and lowers the parts count.



CLAMPING ARRANGEMENT

A clamping plate (blue) bears up on the back of the input shaft and the output disc bears up on this.

High pressure oil is supplied from an external pump. The pressure in this line is controlled by the torque reaction pads.

Annular face seals (green) located in grooves in the output disc bear up on the underside of the clamping plate. These seals are designed to be just at a point of leaking when under active pressure. The maximum rubbing speed of these seals in a 430Nm CVT with an input RPM of 6,000 at high gear and a ratio spread of 5.4 is 63.27m/sec.

An output bell housing is connected to the output disc and wraps over the clamping plate. The space between the bell-housing and the clamping plate is full of traction fluid and when rotating the centrifugal force creates a positive pressure in this chamber which cancels out the similar effect occurring in the clamping chamber, ensuring that centrifugally induced over-clamping does not occur when operating at high revs.

Clamping

A system is provided that provides a minimal mechanical clamping force via a clamping ring that circulates on thrust needle roller bearings. Several sprung loaded pistons bear on the back of this ring providing the permanent clamping force. When the hydraulic pressure is great enough to overcome this mechanical preload it lifts the pistons off the ring so that from then on the hydraulic force is maintained as directly proportional to the Torque reaction Force.

Ultimate Transmissions set the mechanical preload at a level that produces 0.7GPa maximum stress in the rollers. At this level of stress the life of the rolling contacts is almost 38,000 million cycles, or a theoretical 10,000,000kms. Below this level of contact stress there can be excessive slip.

Creation of Hydraulic Pressure

In a typical system operating at 430Nm in low gear the torque Reaction Force on each roller is 6,658 N. This is supported on reaction pads 25mm. in diameter. The pressure required is 13.57MPa (1,800psi approx).

The chart maps the reaction pad and clamping seal sizes using a traction coefficient of 0.055 in low and high gear. This increases to 0.065 in 1:1 ratio when using the internal ball system.

The leakage from under the reaction pads and under the seals at this pressure will be of the order of one litre a minute.

The gap under the reaction pads when leaking at this rate can be controlled at around 40 microns.

Power consumption at 1,000cc./minute @ 2,000 psi is 280 W operating at 80% efficiency.

This power can be provided by a geared electric motor delivering 2.6 Nm. at 1,000RPM. Or a 270 W motor.

The hydraulic pump size will be 1cc./rev.

TRF	6,658	N
TR pad area	491	sq.mm.
Pressure required	13.57	N/sq.mm.
CLAMPING FORCE	205,443	N
Clamp area	15,138	sq.mm.
Radius of inner seal	25	mm
Radius of outer seal	74	mm
Area of outer	17,195	sq.mm.
Area of inner	1,963	sq.mm.
Net area	15,232	sq.mm.

Clamping

A Torotrak system using torque control must be capable of moving the equivalent of these rollers around 20 mm in one second when the CVT is being input at 1,000RPM .

Using the same parameters the flow rate required is according to this table.

RF	**6,658**	**N**
TR Piston area	491	sq.mm.
Pressure required	13.57	N/sq.mm.
Number of rollers (equivalent)	4	
Speed of movement	1	second
Movement of rollers	40	mm.
Flow at 1,000RPM	4.7	litres/min

At 6,000 RPM this flow increases to 28.28 ltr/min and will consume over 8 KW of power. In a system operating at 200KW this is a direct 4%. loss.

If a torque control system is adopted using an active TRFR trunnion the pump size will increase somewhat because it must now provide an active displacement of an actuator piston against a control pressure. The size of the pistons in this system however can be as small as practical and the flow rates can be kept at less than 25% of those in a typical Torotrak variator.

However a torque control strategy is not recommended by Ultimate Transmissions.

Materials

The only special materials required to produce Toroidal Variators are the very high quality bearing steels common to all heavily loaded bearing applications.

These materials are now readily available from leading bearing companies, and steel suppliers.

Work carried out by NSK in 2001 using higher grade steels and in clean environments using higher grade lubricants has significantly extended the expected life of rolling elements as can be seen in this graph (a).

Even when stresses are quite high the contact stress cycle limits can reach cycles giving most automobile applications a design life of well over one million kms.

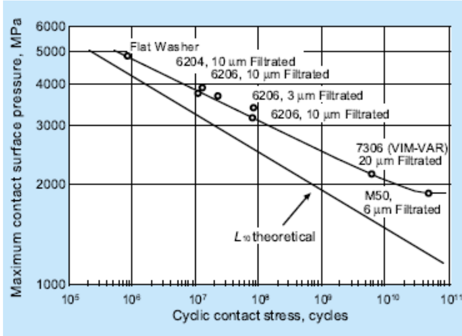
Rolling element bearings are typically more reliable than gears when the lubricant is maintained very clean and machining tolerances complied with.

When the lubrication fluid is extremely clean the type of failure expected is from subsurface flaking which is initiated around metallic oxide inclusions.

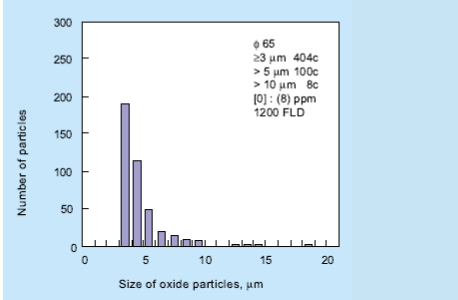
When the stress in the material dependant on material purity is below a certain limit then the life of rolling elements can increase by 100 times the theoretical limit. This limit is referred to as the fatigue load limit.

NSK have tested various material types with a known level of oxide contamination. In the tables (b,c) Material “L” is a low grade competitor bearing and Material S is NSK’s standard material. These tests have established the fatigue load limit.

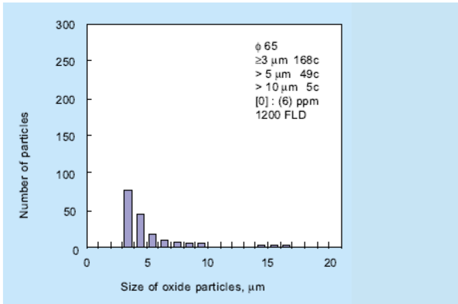
a



b



c

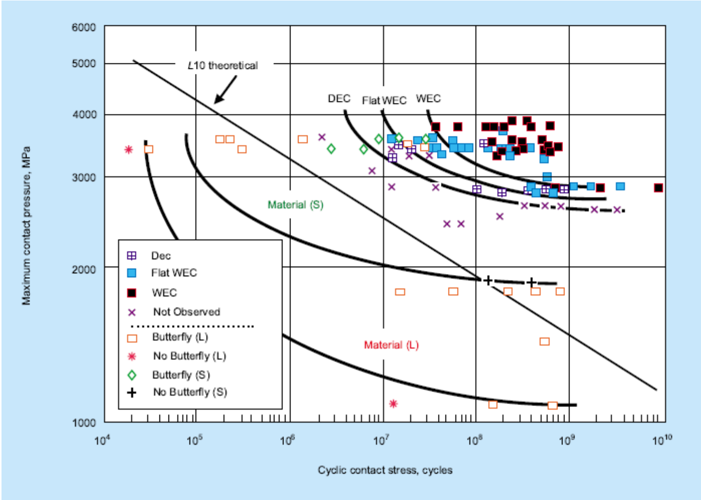


Materials

The life performance graphs are shown right.

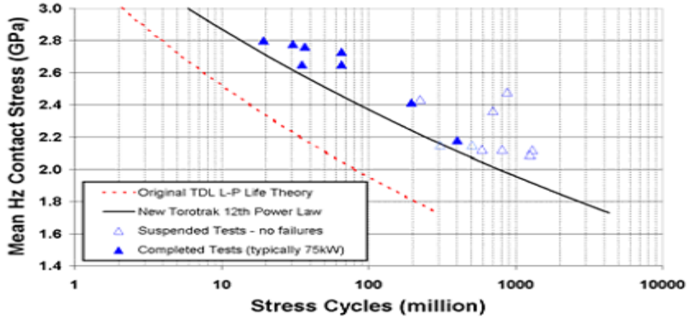
NSK have developed extremely purified bearing steels (SUJ2EP) to improve resistance to subsurface flaking. Other steels (Super TF & Hi TF) have been introduced to resist surface-originated flaking.

They have established the fatigue load limit for these steels as being in excess of 1.5GPa and have tested roller bearings at a Maximum Stress of 1.7GPa for over 80 times their theoretical life.



Torotrak carried out similar research in collaboration with Shell and Jtekt and arrived at a basic life prediction of 380,000 stress cycles when the mean contact stress is 2.1GPa (3.15 GPa maximum) using normal bearing steels.

Indeed, Torotrak working closely with JTEKT and Shell, have significantly improved the durability of the full-toroidal variator by understanding the influence of traction fluid on the variator fatigue life [4,5]. Based on the results from Figure 2 a new conservative 12th power law model, reflected by modern bearing steels [14], using a base life of 380 million cycles at a mean contact stress of 2.1GPa is now used by Torotrak.



Extract from a joint paper by Torotrak and Jtekt.

Materials

It is generally considered that the maximum allowable stress for these steels is 4.2 GPa.

NSK have published papers indicate that forging steel billets into the rough shape to produce toroidal components produces better results than simply machining.

Surface finishes must attain a polish equal or better than that of a normal bearing.

Although the stresses being experienced by a traction roller include shear not present in normal bearings there is little indication that this lowers life expectancy, provided overheating and gross slip does not occurr.

YouTube links

http://www.youtube.com/watch?v=E6LxSiBlFzQ&feature=related

Traction Fluids

The following extract from a paper called “EHL’s: - The secret behind CVT’s: written by Manuel E. Joaquim, of Findet Corporation. It describes the role of traction Fluids in a traction drive very well.

The basic principle of a CVT is that power is transferred by friction contact between two essentially smooth surfaces, rather than by toothed gears.

Some light-weight automobiles are already using CVTs of a type in which power is transferred by a belt in contact with one or more pulleys. But CVTs that use belts (or sometimes chains) are limited to fairly light vehicles, usually those weighing under 2,000 pounds. The Ford Festiva uses a CVT, as does the Subaru Justy. In the light passenger vehicles they are now being used in, CVTs provide high efficiency and thus boost fuel mileage while reducing emissions.

More robust CVTs suitable for heavier autos and for trucks use balls, cones, or toroidal (doughnut-shaped) elements rather than belts or chains. Both types of CVTs are also used in snowmobiles, go-carts and ATVs.

In one of the many varieties of CVTs rollers meet the input shaft at an angle. When the rollers are tilted more toward the input shaft, the speed decreases;

when they are tilted away from the input shaft, speed increases. Traction occurs at the contact between the roller and the shaft. In other CVT designs, the traction occurs between a cone and a ring, or between a ball and a disk, or between a toroidal element and a roller. Nearly all CVTs are also classified as traction drives (think of traction as ³useful friction´) because they transfer power by smooth-surface contact rather than by gears, chains, belts, or pulleys.

In all of these designs, there are two forces at work. One is a normal force in which one element (such as a roller) is pushing down onto a second element (such as a toroidal element). The second is the tangential force, the lateral motion by which one element transfers power to the second element. The tangential force divided by the normal force gives the traction coefficient of a given design. The traction coefficient measures the efficiency of power transfer between the two elements.

There must obviously be some lubricant between the two elements, which would otherwise burn out and fail rather quickly. But the lubricant must not only lubricate, it must also serve as a medium for transferring power, since the two metal elements are not in intimate contact. Three classes of lubricants are available for use in CVTs: boundary lubricants, hydrodynamic lubricants and elastohydrodynamic lubricants/fluids, or EHLs.

Traction Fluids

In boundary lubricants, the lubricating film is sheared or ruptured under high pressure. Hydrodynamic fluids (ordinary transmission fluid is a mixture of both hydrodynamic and boundary lubricants) tend to maintain a film of oil on the surfaces of the two metal elements. Under low forces, this film remains in place. When the forces become too great, hydrodynamic fluids tend to shear. The opposing elements undergo gross slippage, and surface damage to the metal elements is likely to occur.

Since the two metal elements in CVTs are curved rather than flat, the area of contact between the two elements is very small, so the ability of the lubricant to transfer power is important. Unfortunately, hydrodynamic fluids have a relatively low traction coefficient. They are used in the CVT in the Subaru Justy, but because of force limitations are unsuitable for more robust CVTs. In theory, a CVT using a hydrodynamic fluid as a lubricant could be built, but in order to limit force per unit area the transmission would become so large that it would be uneconomical to manufacture and too large to install in a vehicle.

EHLs have higher traction coefficients and behave very differently. Under the high normal and tangential forces needed for transmissions in heavier vehicles, the film of EHL on a metal surface is actually much thinner than the film of a hydrodynamic fluid would be. But where the two metal elements are in rolling contact, the EHL briefly ceases to be a fluid and turns into a glassy solid. The thickness of the solid is minute - about 10 micro- inches - and the solid state lasts for only a few microseconds. As rotation carries the EHL out of the contact area, it immediately becomes a fluid again and regains its normal properties.

But during the brief period as a solid, the EHL actually stops being a lubricant and becomes part of the machinery. By doing so, it achieves a much higher traction coefficient than is possible for any hydrodynamic fluid.

EHLs have the highest traction coefficients of any known lubricant. In tests where both EHLs and hydrodynamic fluids are applied to the same surfaces under the same conditions, the traction coefficients of hydrodynamic fluids are usually between 0.05 and 0.06, while the traction coefficients of EHL are typically 0.1. EHLs are between 50% and 100% more efficient at transferring power than hydrodynamic fluids.

Since the reasons behind CVT development are greater fuel efficiency, improved driving comfort or feel and reduced emissions, this difference is very significant. Traction coefficient, by the way, is not the same as mechanical efficiency. In two transmissions having identical designs, the mechanical efficiency of the transmission using an EHL will be 50% to 100% greater than the mechanical efficiency of the transmission using a hydrodynamic fluid.

Traction Fluids

Both EHLs and hydrodynamic fluids can shear if the force applied is too great. What happens is that one element undergoes gross slip with respect to the other element; this condition is called boundary lubrication. Damage to the metal surfaces is likely. During shear, the molecules of the lubricant may actually be torn apart. For example, a 30-weight oil subjected to

excessive shear can be degraded to a 10-weight oil because the long-chain molecules have been chopped up into shorter-chain molecules. An important characteristic of EHLs is that they can tolerate the relatively high forces present in transmissions for heavier vehicles for long periods without shearing.

EHLs differ from hydrodynamic fluids in another way as well. During rotation, the curved metal elements are slightly deformed by the forces exerted on them; this is what the ³elasto-´ part of the name refers to. The deformation is slight - on the order of 0.001 inch - but it has an important result: the area of contact between the two metal elements becomes significantly greater, since the two elements are very slightly flattened.

Greater area in turn means that there is a significant variation the force per unit area.

The ability of EHLs to become solid under force also plays an indirect role in extending the life of the metal elements in a CVT. One of the common failure modes is the formation of minute surface cracks. A fluid lubricant

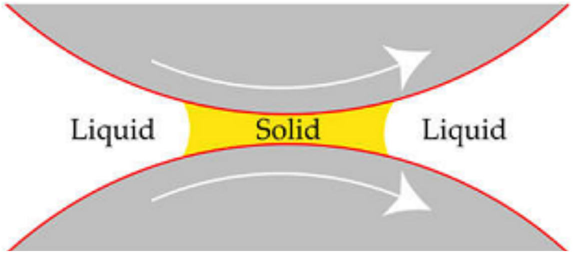
very efficiently transmits both force and vibrations down into the cracks, and causes the cracks to grow. But an EHL, which becomes a solid at the moment of contact, is much less efficient at transmitting force and vibrations. Surface cracks can develop on the metal surfaces of a CVT using an EHD lubricant, but the cracks will grow far more slowly.

EHLs have one other attribute not shared with other lubricants: they run very quietly. They are so quiet that they have been used for years by the U.S. Navy to lower the sound output of underwater equipment. In crowded Japan, EHLs have become popular for use in motorcycle transmissions for the same reason: to lower the noise level.

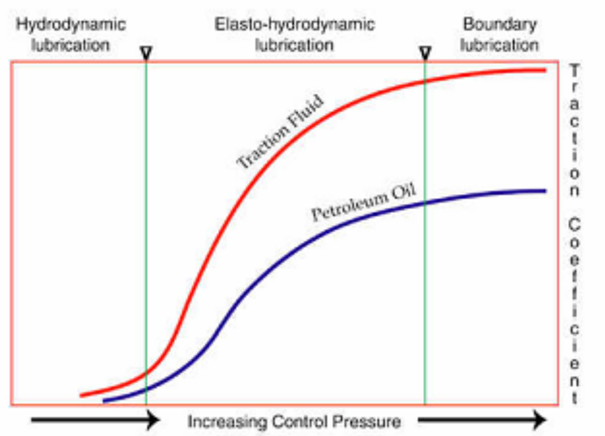
Current applications for EHLs are spread over a number of industries and applications; consequently, they are classified as specialty lubricants and are fairly expensive. But their high traction coefficient makes them the lubricant of choice for autos and trucks using CVTs. Santotrac (www.santotrac.com), the chief supplier of EHLs, predicts that the price will

fall significantly as this market grows. EHLs will also undergo some molecular tweaking and formulation modification (to improve their performance at extremely low temperatures, for example), but they will be the secret ingredient - the lubricant that turns into a solid and becomes part of the machinery - that turns the long-awaited CVT into an everyday fuel- saving convenience and a new driving smoothness.

Traction Fluids



EHD lubricants turn into a glassy solid for a few microseconds under the high forces present in a CVT. This momentary solid state prevents metal-to-metal contact and greatly increases traction.

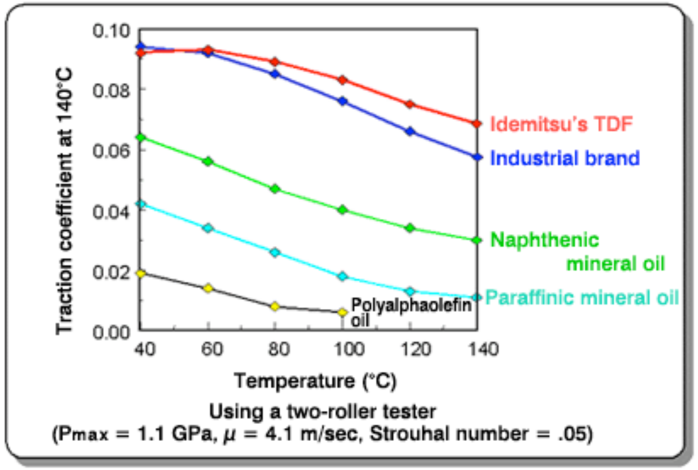


A comparison of behavior of petroleum-based lubricants and synthetic EHLs under increasing pressure. EHLs have a higher traction coefficient across the range of pressures.

Cut-away view of a continuously variable transmission (CVT) under development at Transmission Technologies Corporation.

Traction Fluids

Traction Coefficient Comparison



Nissan SHTV uses an Idemitsu traction Fluid with properties shown in this table.

Idemitsu are much more focused on the effect of heat on traction coefficient. Ultimate transmissions consider that the reduction in traction coefficient due to heating is a critical issue and so design using a more conservative approach to this than does Torotrak.

Refer to "Clamping" for a more detailed discussion on this issue.

YouTube links for information on traction fluids

http://www.youtube.com/watch?v=pDpSerx9nuU&feature=related

Patents & Technical Papers

Ultimate Transmissions are the World leaders in the design and development of Double Roller Full Toroidal Variators (DFTV).

They own all of the patents associated with DFTV itself and the Direct Roller Steering (DRS) method of roller ratio change and the Torque reaction Force Registration (TRFR) using reaction pads.

These patents are in the process of being registered in those countries considered by Ultimate Transmissions to be strategically important to its business.

None of these patents or designs are affected by those patents owned by Torotrak, NSK, Jatco, Jtekt, or CVTCorp.

Technical papers are available on request after registration.

A large number of technical papers on toroidal traction variators are also available on Torotrak's Web site at http://www.torotrak.com/content/56/technical-papers.aspx

These papers, and similar papers on the SAE website detail all of the issues discussed by Ultimate Transmissions on the design of Double Roller Full Toroidal Variators, and IVT using a DFTV as the CVT input.

www.ultimatetransmissions.com.au