

Full-Toroidal Traction Drive Variator Material and Fluid Durability

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ABSTRACT

Full-toroidal traction drives (IVT, TCVT & TVAD) have demonstrated a significant fuel economy, emissions and cost benefits across a diverse range of applications. However, increasing emphasis is being placed on power density and endurance limits, hence additional demands are being placed on the ability of the variator elements and traction fluid to withstand the heavily loaded rolling contact fatigue conditions within the variator. This paper describes the experimental work done to demonstrate the high temperature durability of traction fluid and variator disc and roller material. In addition, the latest fatigue endurance limit testing results are presented which provide further evidence of traction fluid ‘fill for life’

INTRODUCTION

Due to increasing concerns regarding global warming, dwindling oil reserves and ambient air quality, the energy efficiency and emissions from all types of powertrain systems are a major concern. Traction drives, whether infinitely variable (IVT) or toroidal continuously variable (TCVT), allow de-coupling of the engine speed from the transmission output speed thus enabling highly efficient powertrains capable of reducing emissions and enhancing performance. Potential energy savings of up to 20% over vehicles with conventional transmissions have been reported [1, 2].

Currently, all mainstream vehicle continuously variable transmissions (CVTs) in use are belt drives with limited torque capability; hence they are only used with relatively small capacity engines. The Torotrak traction drive transmission on the other hand, is based on transmitting drive-train forces through the shear stresses developed in elastohydrodynamic lubrication (EHL) films generated

between the rollers and toroidal discs that are part of the variator. The performance, durability and efficiency of such a transmission, are determined by the rheological properties of the lubricant under the conditions that exist in the EHL contacts and the material properties of the disc and rollers. With today's range of traction fluids and disc & roller steels, this type of transmission offers much higher torque capability than conventional CVTs or significantly lower cost. Hence, the full-toroidal transmission is a simple variable drive technology with many applications ranging from low-power TCVT ancillary drive-units through to IVT multi-regime transmissions suitable for passenger cars, SUVs, buses, trucks and Off-Highway vehicles.

Fully exploiting the features of an IVT offers significant further benefits above the headline fuel efficiency gains. Engine designers are offered a new freedom to consider optimized combustion cycles or constant speed engines. Vehicle designers can implement downsized engines or hybrid power sources.

As with all transmission technologies, there is continual emphasis on cost, package and weight reduction. This places increasing demands on the variator disc & rollers and the traction fluid to withstand the heavily loaded rolling contact conditions and the corresponding high contact temperature.

IVT ROLLING CONTACT FATIGUE (RCF)

As described elsewhere [3, 4, 5] Torotrak (Development) Ltd (TDL) uses a fatigue life durability model for the variator based on a number of complete full-size variator fatigue tests and the classical Lundberg-Palmgren method [6] governing point contacts found in gears and bearings where by:

$$L \propto \frac{1}{\sigma^9} \quad (1)$$

where L is the life and σ the contact stress.

It is recognised that the Lundberg-Palmgren approach has limitations even when applied to bearings and gears; the main limitations being:

1. no concept of possible infinite fatigue life [7]
2. elastohydrodynamic lubrication (EHL) pressure distributions being significantly different from the pure Hertzian distribution especially with rough surfaces [8]
3. no accommodation of surface shear stresses [9]
4. no account of operating temperature, its affects on material or lubrication properties [10]
5. no consideration of microstructural alterations and residual stresses developed during operation [11].

In addition, it is accepted that there are major differences between the contacts considered by Lundberg-Palmgren and an IVT contact, these being:

- Significantly increased surface shear stress, i.e. traction in the IVT contact, which alters the sub-surface stress distribution.
- Reduced contact conformity and hence reduced film thickness in the IVT contact.

There is a difference of opinion regarding which sub-surface stress effectively controls rolling contact fatigue. Whichever sub-surface stress is considered detrimental, the effect is to move the position of maximum sub-surface stress towards the surface and increase the probability of a surface initiated failure occurring. This is exacerbated by the thinner film thickness seen in IVT contacts due to reduced contact conformity and particularly when the contact temperature is high, i.e. when the variator is subjected to high powers.

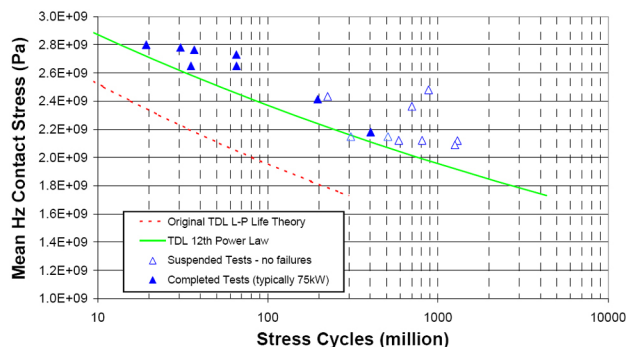


Figure 1. S-N Curve

Despite these limitations and differences, the results of a number of full-sized variator fatigue tests (Figure 1) using traction fluids from Shell and disc and rollers from JTEKT have shown very good agreement with the Lundberg-Palmgren method above, using a base life of 380 million cycles at a mean contact stress of 2.1GPa.

Concerns regarding the durability of full toroidal variators, due to high thermal mechanical surface stress from increased contact spin, and the affects of such temperatures on the disc & roller and traction fluid life continue to be raised in the literature [12, 13]. It is from this background that the following work was undertaken to investigate the high temperature durability of the full-toroidal variator. At the same time a number of long term fatigue durability tests have been undertaken to investigate the applicability of an endurance limit on the disc and rollers. The fatigue endurance tests were undertaken at 1.78GPa, 1.91GPa & 2.03GPa

EXPERIMENTAL TEST SET-UP

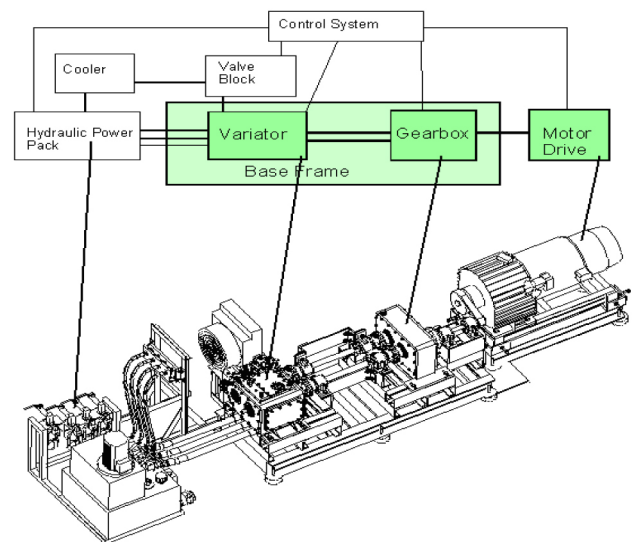


Fig. 2. Variator Module Test Rig

The data presented in Figure 1 and the currently reported results were carried out on a power re-circulating four-square test rig, shown in Figure 2, which incorporates a 100mm (roller OD) full-toroidal variator test module. Hence real contact geometry and operating conditions could be used. The ratio (R_v) of the input disc speed to the output disc speed was set via the rig gearbox; testing being conducted at $R_v = -0.998$ such that the contact conditions on either side of each roller were very similar. The same nominal endload (axial clamping force) was used for the variator material durability tests, the roller conformity (ratio of roller crown radius and roller radius) being changed to obtain the required contact stress. Three conformities were used, namely, 0.24, 0.38 and 0.5, by changing the roller crown radius. The rotational speed and torque, of both the module mainshaft (containing the disc

and rollers) and the module lay shaft, were measured. The RMS vibration level of the variator module was measured using an accelerometer. All test rig data including traction fluid pressure, temperature and flow rate were recorded via a Keithley data acquisition system. The geometrical dimensions of the test pieces (disc and rollers) used in the current work were as shown in [Figure 3](#). Disc and rollers were made from KUJ7 material [14] with $Ra < 0.1$

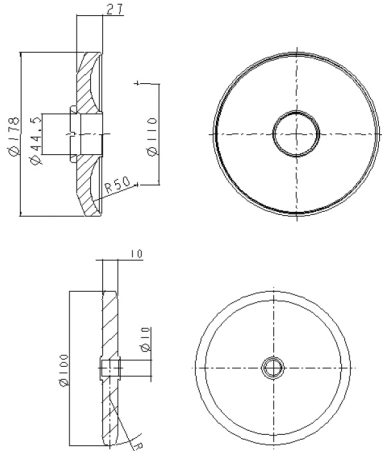


Fig. 3. Geometry of Test Disc and Rollers

HYDRAULIC SYSTEM

A Shell prototype traction fluid was used for all tests. Rheological properties of this fluid are currently confidential. Traction fluid was used to lubricate, cool and control the variator. A separate hydraulic power pack enabled independent supply of the roller carriage piston reaction pressures, endload and lubrication cooling flows.

A water to oil heat exchanger supplied with chilled water controlled the temperature of the traction fluid lubrication cooling flow. The chilled water flow rate was controlled via an electronic PID controlled valve, to maintain the desired traction fluid cooler out supply temperature at 80degC for the durability tests and 90 to 100degC for the traction fluid high temperature life testing.

Manually set needle control valves in the hydraulic circuit controlled the flow rate of the traction fluid used to cool the variator. This cooling fluid was feed via the carriage and its piston into shrouds around the roller via two 1.5mm diameter 'jets'. [Figure 4](#) shows the roller shroud and carriage assemblies.

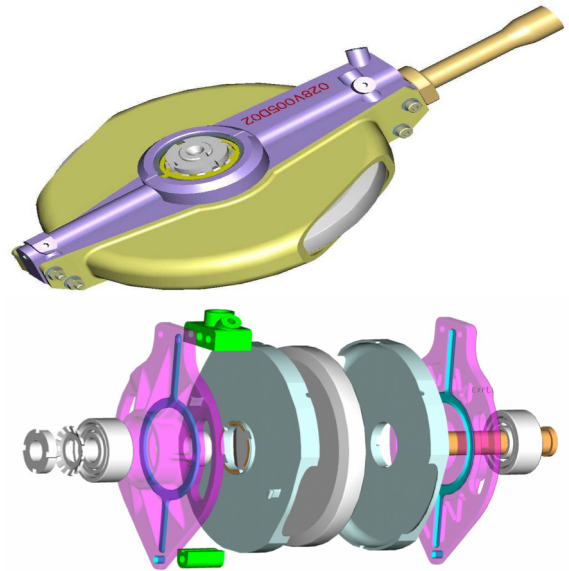


Fig. 4. Roller Shroud Assemblies

Each roller was fitted with a rubbing K-type thermocouple just after the disc/roller contact, such that the thermocouple measured the roller crown metal temperature.

TRACTION FLUID DURABILITY TEST CONDITIONS

In order to assess traction fluid durability, a three part test program was developed. The first part investigated the influence of very high variator component temperature on fluid life. The second part investigated the influence of longer-term contact shear combined with high bulk oil temperature on fluid life. The final part looked at the effects of very long-term contact shear from a 2 year fatigue endurance test on fluid life. For each part, new traction fluid was used whilst the same variator disc and rollers were used for parts 1 and 2, with new disc and rollers utilised for Part 3. The traction properties (along with industry standard bench tests) of new fluid and samples of fluid taken after each test were measured.

PART 1

In order to assess the affects of very high variator component temperatures, a 50-hour continuous, non-stop very high temperature variator test (245degC roller crown metal temperature throughout the test) was developed. The traction fluid variator cooling flow was reduced to obtain the required temperature. The test conditions used are given in [Table 1](#).