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2000-01-1872

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International Spring Fuels & Lubricants
Meeting & Exposition
Paris, France
June 19-22, 2000

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ISSN 0148-7191
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Printed in USA

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The Effect of Lubricant Temperature on the Loss Mechanisms Associated with an Automotive Metal V-Belt CVT

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ABSTRACT

Belt drive continuously variable transmissions (CVTs) have been on the market for a number of years now, and should in principle offer increased fuel efficiency over similarly sized fixed ratio transmissions. However, to date the reduced fuel consumption and emissions predicted for CVTs has not been realised by production cars. A contributing factor is that CVT systems have a lower efficiency than their fixed ratio counterparts. This reduced efficiency has been linked to an increased number of inherent losses associated both within the belt mechanism itself, and the hydraulic control system.

Experimental work has been undertaken to investigate the no load and low load torque losses associated with a pushing V-belt CVT at a range of lubricant temperatures. This was done using a specially developed test rig. This has allowed the effects of the individual loss mechanisms to be investigated in isolation. The work has been further supported by the development of a second test facility to investigating the belt slip that may occur in the belt drive CVT.

This paper will discuss the findings from the experimental work, in particular the effects of lubricant temperature on the individual loss mechanisms. The work will highlight how the viscosity and friction properties of the lubricant have a significant effect on the losses and how an improved understanding of these losses could lead to improved vehicle efficiency.

INTRODUCTION

The efficiency of a vehicle transmission system is an important factor in the overall efficiency of any vehicle, and with the increased environmental constraints which todays vehicles must reach, in terms of emissions and fuel consumption, it is important to understand where the inefficiencies lie within a transmissions design. Belt drive CVTs have been on the market for a number of years now, but have so far not managed to show the improved fuel economy over similarly sized fixed ratio transmissions that had been predicted.

By effectively having an infinite number of gear ratios the CVT should allow better matching of the engine operating conditions to the variable driving conditions that a vehicle may experience. Thus a typical CVT system might be controlled so that the engine can be constrained to operate as near as possible to its maximum efficiency point. Since the control strategy for reduced fuel consumption is well founded it can be concluded that existing CVT systems have a lower efficiency than their fixed ratio counterparts.

This inefficiency has been linked to a number of possible inherent parasitic losses **[1]** associated with pushing V-belt CVTs, namely torque losses within the belt mechanism itself, belt slip and hydraulic control system pumping losses. These major losses exist alongside the normal losses associated with fixed ratio transmissions, namely gear meshing losses, bearing losses, oil churning and windage.

Previous work by the authors **[2]** has described the development of a test rig for measuring the torque losses though a belt drive CVT at very low power levels. Initial results from this work indicated that the lubricant temperature and thus viscosity, has a very significant effect on the torque loss mechanisms.

For automotive engineers this has added significance when it is considered that existing drive cycle testing legislation requires ambient temperature starts to tests, while proposed legislation may include sub zero start condition, where viscosity dependant parasitic losses will increase considerably.

THE TRANSMISSION

The transmission being investigated is similar to that currently used in Rover 25 and 45 automatic cars and in the ‘steptronic’ MGF. It is based on the Van Doorne pushing V-belt variator system. This system is based on a steel V-belt running between two pairs of steel pulley sheaves. One half of each pulley is able to move axially under a hydraulic control pressure, thus forcing the belt to run at a different radius and hence different ratio. The hydraulic control pressures are modulated to supply higher clamping forces at higher torque transfer levels. The belt is constructed from several hundred segments held together by steel band sets. In operation the bands operate in tension, while the torque is transferred by compressive force between the belt segments. A more detailed description of the function of a metal V-belt CVT is given by Hendriks et al. **[3]**.

CVT LUBRICANTS

Lubricants used in CVTs have a large number of performance characteristics to satisfy, such as lubrication, heat transfer, clutch engagement, pumpability and traction transfer. Added to this is the need for the lubricant to reach the same 'fill for life' characteristic that is expected by the modern automobile customer **[4&5]**. Some of these functions require contradictory requirements from the lubricant. The original CVTs functioned on standard ATF formulations. Since then oil companies have targeted new lubricant formulations at increasing the torque capacity of the belt drive CVT. This is achieved by the addition of traction additives **[6&7]** to the lubricant. Conversely these could have the effect of decreasing the efficiency of the transmission, by increasing the coefficients of friction between other surfaces in relative motion to each other. There has to be a careful balance between increasing the traction properties of the fluid and thus being able to reduce the clamping pressure in the system, and increasing the losses within the belt mechanism.

MEASURING THE LOSSES

TEST METHODS – The results described in this paper were measured experimentally on two different test rigs: a torque loss test rig **[2]** and a belt slip test rig. The torque loss testing can be defined into two distinct methods. Namely, steady state testing, and temperature transient testing.

In steady state testing all the test rig parameters were maintained continuously during the period in which test data was acquired. In temperature transient testing the test rig was set to pre selected speed and load conditions, and then data was acquired throughout the transmission warm up period. The steady state tests were performed at nominal temperatures of 25°C, 50°C, 75°C and 95°C.

The steady state testing was later repeated at the same temperature conditions with components being removed from the transmission so that their individual loss mechanisms could be measured.

The belt slip testing was performed using the rig described later in this paper. In this case the output torque is gradually increased at fixed input speed and control pressure conditions and the relative speeds of the belts and pulleys are monitored.

EXPERIMENTAL RESULTS

TEMPERATURE TRANSIENT TORQUE LOSS – Figure 1 below shows a typical result for temperature transient test condition. It can be seen that the input torque at first decreases as the transmission begins to warm up, as expected. Then the losses begin to increase as the temperature increases further. When a predetermined temperature is reached the cooling to the transmission is turned on and the torque losses recorded as the transmission cools. The results eventually form a loop, meeting identical points on cool down and warm up. The loop is believed to be a hysterisis effect caused by the large heat capacity of the metal components in the transmission, such that the bulk temperature during transients is not the true temperature at the belt and pulley interfaces.

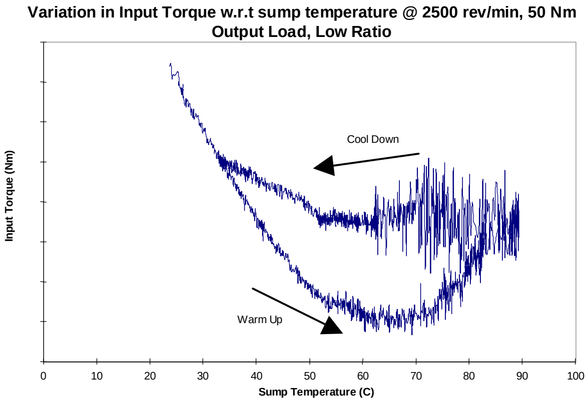

Figure 1. A typical temperature transient test result

STEADY STATE TEMPERATURE RESULTS – Initial steady state testing showed good repeatability with similar temperature dependant results confirming the increase in torque loss seen in the temperature transient tests. The steady state torque loss results were further supported by back to back comparison tests with a second transmission, where there was a maximum error of 1 Nm between the two transmissions at the same operating conditions.

BREAKDOWN TEST RESULTS – Figure 2 & Figure 3 below show some typical results of the breakdown tests in low and high ratio respectively. The process of breakdown testing was firstly final drive removal, followed by the belt and the pump, leaving the input shaft to be tested in isolation.

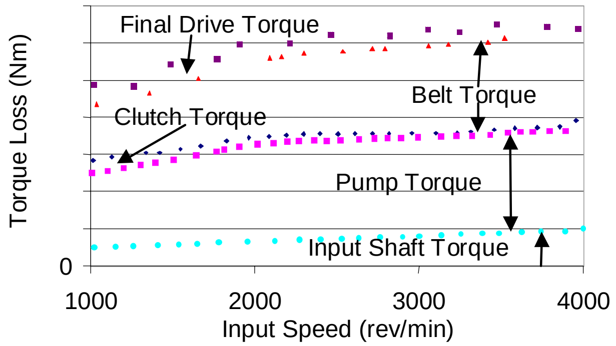

Figure 2. A typical breakdown test results in low ratio

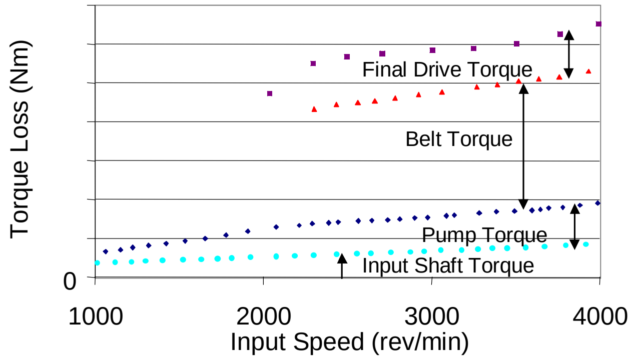

Figure 3. A typical breakdown test results in high ratio

The breakdown tests above were repeated at the 4 steady state temperature conditions. Clearly the input shaft torques are identical in both conditions, but in low ratio the pump torque loss is up to 3 times greater in magnitude, due to the higher pumping pressures, while the belt torque loss is considerably reduced. It can also be seen that the final drive losses are much more significant in high ratio, this is due to the increased speed of the final drive and the ratio effect inferring more torque to the input shaft.

In the low ratio tests the two lines between the belt torque loss and pump torque loss are tests performed with and without the reverse clutch assembly installed. The difference between the two lines is effectively the drag torque on the disengaged reverse clutch. It can be seen that this is very small and in fact only significant at tests below 25°C.

From the individual breakdown tests it was possible to calculate the torque loss due to each component. Figure 4 & Figure 5 below show the variations in belt torque loss with temperature for low ratio and high ratio respectively. In both cases the torque loss in the 25°C test is clearly less than at the other temperature conditions, while in high ratio the 50°C test is also less than the 75°C and 95°C tests. It is believed that this increase in torque loss is due to the lubrication regimes in the belt changing from a hydrodynamic regime to a mixed/boundary lubrication regime.

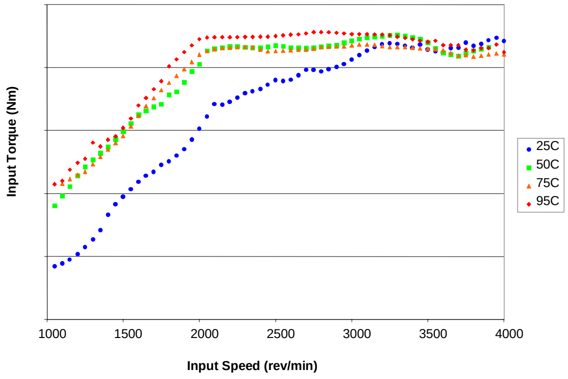

Figure 4. Belt torque losses in Low Ratio

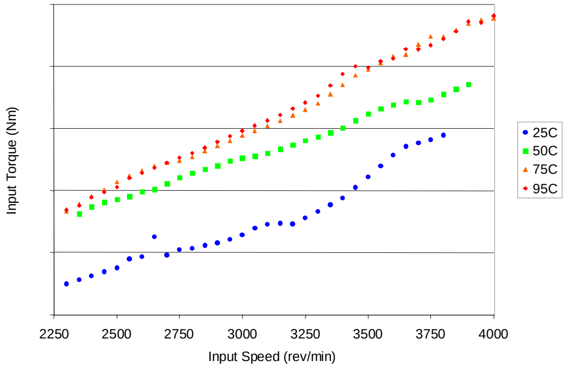

Figure 5. Belt torque losses in High Ratio

The high ratio results appear to hold the lower loss regime longer since the relative speed in the belt are higher thus assisting oil film formation. In low ratio the initial steep gradient of the lines up to 2000 rev/min is due to the increasing clamping pressure being applied by the hydraulic controller, after 2000 rev/min the clamping force begins to reduce slightly. In high ratio the clamping pressures are more constant and the gradient of the lines therefore indicates a speed dependent effect on the torque loss. Figure 6 below shows the variation in the torque loss component of the input shaft with respect to temperature and speed. It can be seen that the input shaft torque loss is effectively linear with speed and viscosity dependent. If the results are plotted 3 dimensionally against viscosity a simple curve fit can be applied to the input shaft losses.

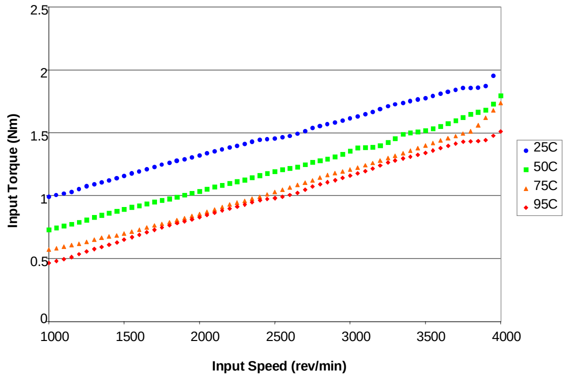

Figure 6. Input shaft torque losses

VARIATOR TEST RIG

Following the work carried out with the original test rig, it was clear that further work needed to be undertaken to investigate the effects of belt slip that may be occurring in the belt mechanism. Not only is the belt slip an inefficiency, but a knowledge of the functioning of any belt slip would lead to an improved understanding of the of the torque loss mechanisms that are occurring in the belt, and the lubrication regimes existing between the belt and pulley interfaces. The test rig was designed and built to test the mechanism of the belt in isolation, with independent control over the belt ratio and clamping pressures. The new rig also allowed testing at much higher output torques than were possible on the original rig to instigate higher levels of belt slip.

The variator rig is shown schematically in Figure 7. A hydraulic axial piston motor, supplied by a hydraulic ring main facility, drives the rig, and a variable displacement axial piston pump unit then loads the belt, by modulating its pressure. The rig is instrumented to record output torques up to 400Nm at the secondary pulley, equivalent to 2000Nm at the final drive, while the maximum speed is limited to 3000rev/min at the input shaft. The technique for measuring the belt slip is described in more detail below. The control pressures were supplied by an independent hydraulic circuit.

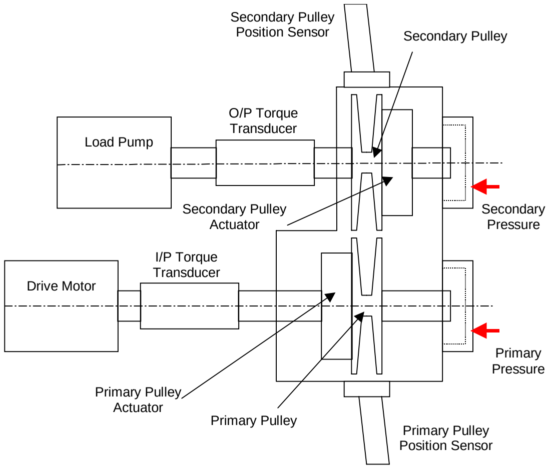

Figure 7. Schematic of the Belt Variator Test Rig

VARIATOR RIG INSTRUMENTATION – The aim of the variator test rig was primarily to measure the slip losses that might exist in the metal V-belt. Therefore the rig was instrumented accordingly.

<u>Variator Speed Ratio Measurement</u> – The variator test rig allowed for highly accurate measurements to be made of the speed ratio through the variator. Magnetic pickup speed sensors were used on the input shaft, output shaft and to detect the belt speed by counting the segments on the belt as they pass. To increase accuracy the speed data was collected in a pulse format using 3 digital counter/timer units, all triggered simultaneously. Each of the magnetic pickup devices is conditioned using standard frequency to voltage cards; these produce more uniform pulses than the standard output of the magnetic pickup. These pulses were then counted using the counter timers and the results recorded on paper. Each test condition was repeated three times giving highly repeatable results.

<u>Variator Actual Ratio Measurement</u> – The actual belt ratio was measured by recording data from two radial probe units fitted with LVDT (Linearly Variable Differentiating Transformer) position transducers about each of the pulleys. The LVDTs were scaled so that they operate around their most linear region and so that they were highly sensitive. For each ratio condition the LVDTs were relocated to operate around their central position. The LVDT assemblies proved to be highly accurate and very repeatable

Figure 8 below shows a typical result that may be recorded from the rig. The radii calculated from the speed ratio are plotted against the radii calculated from the LVDT data. From the data it can be seen that as the output torque is increased the primary radius decreases and the secondary radius increases, thus the transmission effectively moves to a lower ratio. The error between the speed derived radii and LVDT derived radii can be calculated as a percentage slip or tangential slip speed on each pulley, as shown in Figure 9 through to Figure 11.

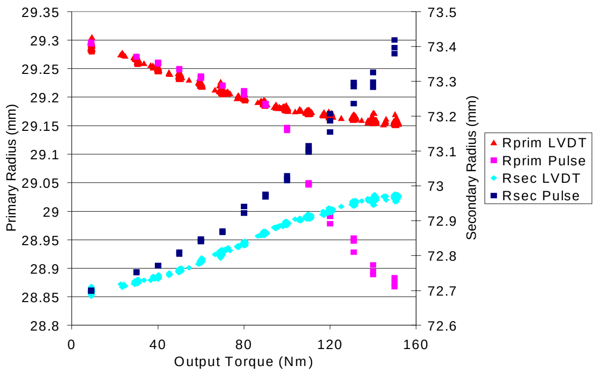

Figure 8. Typical Ratio change effects in Low Ratio

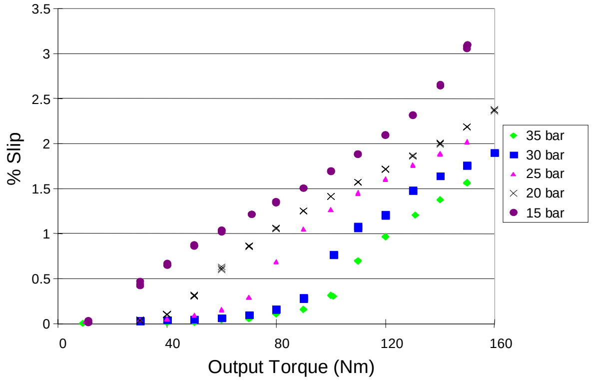

Figure 9. Effect of Clamping Pressure on Belt Slip in Low Ratio Tests

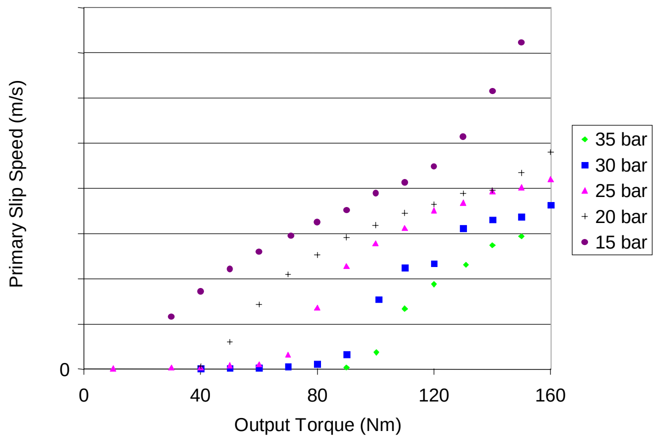

Figure 10. Primary Slip Speed with respect to Output Torque in Low Ratio

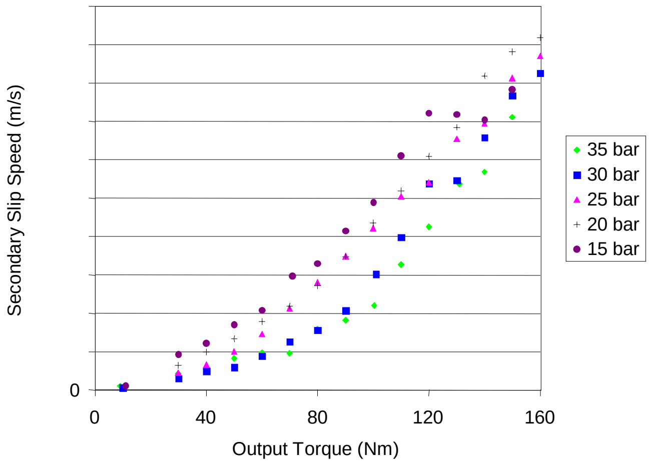

Figure 11. Secondary Slip Speed with respect to Output Torque in Low Ratio

It can be seen from the above results that the inefficiency due to belt slip is significant (up to 3%) and it is therefore important to understand the mechanism of any belt slip. The slip speed results show a very clear dependence on the clamping pressure applied to the pulley actuators. Previous work **[8]** has focussed on a mechanism for belt slip occurring at the primary pulley only. The test work undertaken here has clearly identified a tangential belt slip occurring at the primary and secondary pulleys simultaneously, above an underlying change in belt ratio. The slip at the primary pulley is larger than that at the secondary pulley and is believed to be a function of the angle of wrap about each pulley, and the gap effect described by Kobayashi et al.**[8]**.

PROPOSED LOSS MECHANISMS

This section describes the individual loss components within the transmission, and how these components may be affected by the operating parameters of the transmission.

PUMP LOSSES – One of the major losses within the transmission is the torque absorbed in driving the hydraulic pump. The pump supplies the ratio control pressures and lubrication flow for the transmission. In many operating situations the pump torque is the largest loss mechanism in the transmission. In its simplest form the torque absorbed by the pump can be described using a simple mechanical and volumetric efficiency.

$$T_{pump} = \eta_m \eta_v DP$$

A more detailed analysis including fluid viscosity effects is provided by the Wilson pump model, below, described by McCandlish and Dorey **[9]**. Initial results show that the performance coefficients (C_v and C_f) of the pump are very linear with respect to both pump speed and pressure, as expected the pump losses reduce considerably as the fluid viscosity decreases.

$$T_{pump} = DP + C_v\left(\frac{\mu\omega}{P}\right)DP + C_f DP + T_c$$

BELT TORQUE LOSSES – A number of papers have been written in recent years related to the modelling of the metal pushing V-belt transmission, notably by Micklem et al **[10&11]** and Fujii et al. **[12&13]**. Micklem produced an empirical model for the torque losses in the belt drive.

Micklem proposed a number of specific torque loss mechanisms within the belt. The first and the largest component is a wedging force as the segments are forced into and pulled out of the pulley contact arc. On exit from the primary pulley the belt will be retained by the pulley to a radius smaller than the contact radius, and on entry into the secondary pulley the belt will be forced out to a radius greater than the contact radius. Secondly Micklem proposed a viscous shear film between any belt component having a relative motion to a neighbouring component. Hence, he proposed losses between the segments and the band packs and between individual bands assembled in the band packs.

More recently Fujii et al. have written a number of papers describing experimental work in which a belt has been instrumented with strain gauges to measure segment compressive forces and ring tension variation throughout the belt pulley system. This work indicates that some improvement can be made to the Micklem modelling since a number of assumptions made in the work have now been shown to be incorrect, namely uniform band tension, and a band speed uniformly faster than the segment speed. A number of the above mentioned papers also describe the existence of an idle arc within both pulley wrap angles, in which the compressive load upon the segments does not change. The magnitude of this idle arc will conceivably have an influence on the force loading seen by individual segments as they pass through the loading and unloading arcs. To date no previously published work has been found investigating the effects of fluid properties on the belt torque loss.

New improved models are currently being validated as part of this work that aim to quantify and improve the understanding of the empirical models proposed by Micklem et al. The models are based upon the deformation characteristics of the pulleys and will include an empirical explanation of the temperature dependent changes in belt torque.

BELT SLIP LOSSES – A few papers have been produced discussing the measurement and possible mechanisms of belt slip in metal V-belt drives. Micklem proposed a model based on an EHD Lubrication regime, as the means of force transfer between the pulley and segment sides, this is effectively a model of belt slip. While Kim et al. **[14]**, have measured changes in radial belt positions around the pulley wrap angles, and produced ranges for coefficients of friction to fit slip data. More recently Kobayashi et al. **[8]** have undertaken work measuring and modelling micro slip within the belt system. The work undertaken here has measured slip at both pulleys with a high degree of accuracy, and it is proposed that a model of these losses will be developed in the near future. To date the test work on the variator rig has only been performed at a nominal 50°C operating temperature, further work is required to investigate the effects of lubricant viscosity on belt slip.

OTHER LOSSES – The other loss components within the transmission are the final drive, reverse clutch drag, and input shaft losses. The mechanisms for these losses can be described as meshing losses, churning, and bearing and seal drag. With all of these proposed mechanisms one would expect to see the losses reduce with a reduction in viscosity.

CONCLUSIONS

A number of experimental techniques have been developed that allow accurate measurements of the small torque and speed losses through a belt drive CVT, at a range of temperature conditions.

The experimental results in steady state and transient temperature testing have shown good repeatability. Trends shown in the transient temperature testing have been shown to exist in steady state testing. It has been shown that torque loss through the transmission varies significantly with respect to temperature, and with bulk fluid temperatures in excess of 65°C the torque loss through the transmission can actually increase.

Results from the breakdown tests have isolated the component causing this torque increase and have shown that the torque loss component due to the belt mechanism actually increases as the viscosity of the lubricating fluid decreases.

Further test work on the new variator rig has shown that belt slip occurs in small quantities around both the primary and secondary pulleys. The slip occurs above an underlying change in actual ratio, which decreases as the output torque is increased. Initial predictions from empirical calculations show that the slip speeds measured are too slow to support oil film formation and indicate the existence of a boundary lubrication regime at the belt pulley interface. This is further confirmed by the increase in torque loss associated with decreasing lubricant viscosity.

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