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CONTROLLED VELOCITY ACCESSORY DRIVES – SOLVING THE POWER-AT-IDLE CHALLENGE

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ABSTRACT

Orbital Traction demonstrated through a Phase I SBIR the feasibility of a controlled velocity accessory drive (CVAD) that enables a heavy duty alternator to produce full rated power at engine idle and across the full range of engine speeds. Orbital Traction's CVAD is based on a novel, continuously variable transmission and can be applied to other engine accessories and OBVP applications.

INTRODUCTION

With many types of vehicles, a significant amount of the vehicle drive cycle occurs when the engine is at or near idle. Vehicles that fall into this category include specialty trucks such as garbage trucks, cement trucks and other vocational vehicles; emergency vehicles such as ambulances and fire trucks; and military vehicles, both tactical and combat.

The military in particular is sensitive to vehicle operation at low engine speeds. Many missions call for vehicles to spend significant amounts of time at idle. Still other missions, such as route clearance and certain convoys require vehicles move at very slow ground speeds.

Because engine accessories such as the alternator, water pump, cooling fan, power steering pump and A/C compressor are typically driven directly off the engine via a belt, they are forced to run at some fixed ratio to the engine speed. As a result, when the engine speed is low, the engine accessories are being driven much more slowly than is optimal, either for performance (accessory output) or fuel efficiency. Alternators in particular only produce about 50% of their rated power output at their minimum operating speed.

Orbital Traction is developing variable speed drive systems for engine accessories based on a novel, compact continuously variable transmission (CVT) design. These accessory drives, known as controlled velocity accessory drives (CVADs), enable the accessory speeds to be decoupled from the speed of the vehicle engine. Therefore, when the engine speed is low, the CVAD can be adjusted so that the engine accessory spins at a speed that enables optimal performance and/or fuel efficiency. As the engine speed increases, the engine accessory speed can be held constant, or lowered as required by the application.

THE "POWER AT IDLE" CHALLENGE

The power requirements of tactical military vehicles have consistently increased over the past 30 years. As weapons and communications technologies have advanced, greater and greater demands have been placed on military vehicle power systems. The progression of tactical vehicle power requirements over time is shown in Figure 1.

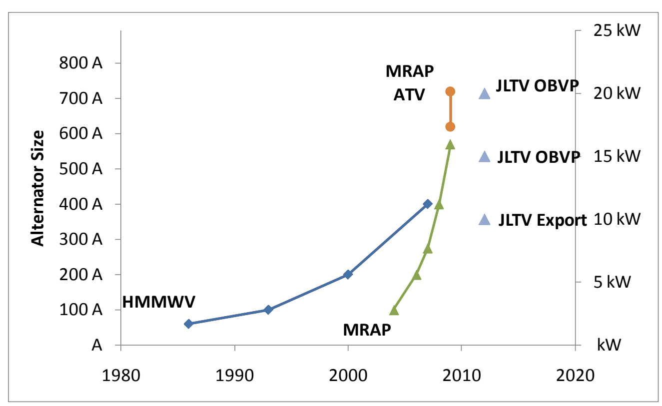

Figure 1: Military vehicle power requirements [1].

Tactical military vehicles spend as much as 50% of their operating time at engine idle. Since the alternator is driven directly off the engine, it operates at low speed while the vehicle is at idle and produces considerably less than full rated power. A typical curve showing alternator output versus operating speed is shown in Figure 2.

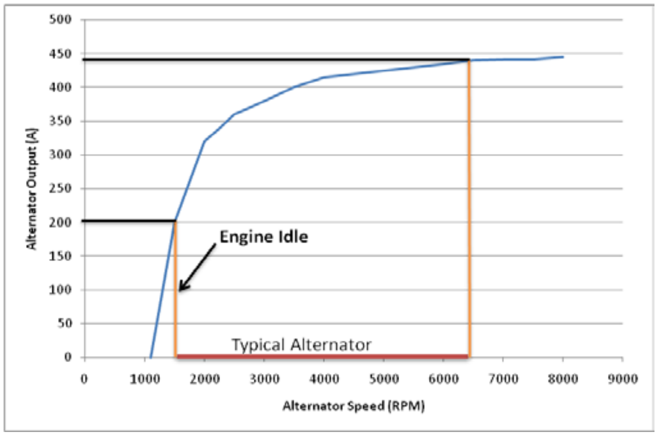

Figure 2: Power curve for a typical 400 A alternator.

An example of the increasing power requirements challenge is the growth of the power demands in the HMMWV platform. The original HMMWVs used a 60 amp (A) alternator, but many of them over time have been upgraded to meet increasing mission requirements. Currently, the standard HMMWV electrical system needs to supply at least 154 A of current at idle to satisfy mission requirements [2]. Since at typical idle speeds the alternator is producing only 50% of rated power, the military has been forced to use oversized alternators, or to operate the vehicle at a higher idle, or both to meet the mission power requirements. The latest armored HMMWVs have been manufactured or retrofitted with a 400 A alternator so that sufficient power is available across the full range of engine speeds.

While these stopgap measures enable the vehicles to meet the increased power requirements, they do so at the cost of greater fuel consumption and additional weight. Both of these drawbacks act to limit the tactical range and capacity of the vehicles on which they are implemented. Furthermore, this practice is approaching the limit of its ability to provide necessary vehicle power at idle, as alternator sizes are reaching practical limits. Current forecasts of power requirements at idle in next generation tactical vehicle platforms exceed the ability of conventional alternators to adequately address the issue.

THE CVAD SOLUTION

Orbital Traction's Controlled Velocity Accessory Drive enables an alternator to generate full rated power at engine idle, and across the full range of engine speeds, by decoupling the speed of the alternator from the speed of the engine. The CVAD-enabled alternator is capable at standard vehicle idle of generating twice as much power as a traditional alternator, without sacrificing performance at higher speeds. An example of the resulting increase in alternator performance for a 400 amp alternator is illustrated in Figure 3.

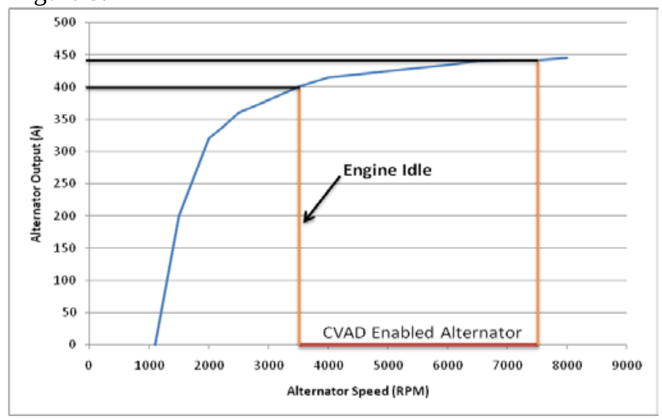

Figure 3: Power curve for a CVAD-enabled 400 A alternator.

In March, 2010, Orbital Traction was awarded a Phase I SBIR from the U.S. Army that funded research relating to two core issues that were perceived to be a challenge in implementing Orbital Traction's continuously variable transmission technology for the CVAD application. Successful completion of that research led to a Phase II award, which began in May, 2011. The Phase II effort will culminate in demonstration of Orbital Traction's CVAD on a VMMD platform in 2012.

PHASE I SBIR RESEARCH

The primary objective of the Phase I project was to demonstrate through modeling and simulation the feasibility of producing a CVAD that would enable an alternator to produce rated power while operating at idle and across the full range of engine speeds based on Orbital Traction's CVT technology. While Orbital Traction's CVT technology is currently used commercially in the oil & gas industry, the technical challenge for implementation of the technology for use with engine accessories lie in ensuring adequate durability for an automotive application, particularly in the face of the torsional oscillations produced by an internal combustion engine.

The platform chosen for the Phase I research was a HMMWV equipped with a 6.5L diesel engine and 400 A alternator. A system schematic was generated to depict the engine-CVAD-alternator system. Based on this diagram, the rotational speeds and torques at the junctions of each component were calculated, assuming full electrical load on the alternator and the efficiency of each component. These calculations provided the basis for the modeling of the

CVAD components, sized appropriately to meet the demands of this application.

To meet the operational requirements of the CVAD, it was necessary to design and scale an appropriate CVT geometry. Orbital Traction's CVT technology, known as the Milner CVT or MCVT, consists of a number of planets (balls) rolling between a set of inner and outer races such that it is analogous to an epicyclical gear set with variable ratios. The CVAD sits between the alternator belt and the alternator. When configured as a speed increaser, as required for the CVAD application, the alternator belt drives the MCVT planet carrier, causing the planets and, in turn, the inner races to rotate. The inner races are coupled to a center shaft which serves as the output of the CVAD. The relative position of the outer races determines the ratio between the inner races and the carrier rotation. Figure 4 depicts the relationships among the various components.

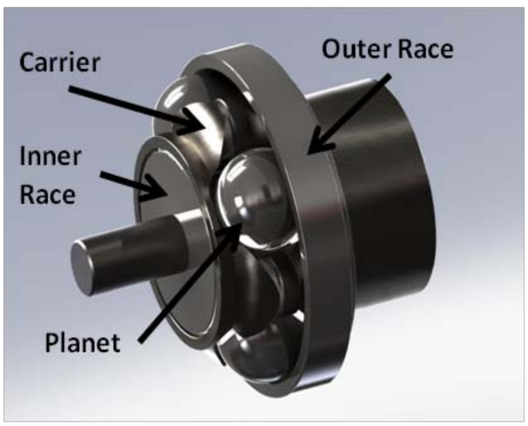

Figure 4: Key CVT components.

Torque is transmitted through the system at the points of contact between the races and the planets. The geometry of the device determines, among other things, the size of the contact patch at which torque transfer occurs. This contact patch size affects the power capacity, efficiency, and life of the system. The geometry of the races and planets also has a direct effect on the range of ratios for the CVAD, as well as the amount of power that can be transmitted through the device. Geometry selection is therefore a balance between the desired packaging envelope, the operational ratio range, the power and torque rating, the power transmission efficiency, and the expected life of the CVAD. For instance, desire for a smaller packaging envelope will necessitate the use of smaller diameter planets and races, which will lead to higher stresses at the contact patches and a shorter device life than a device with similar power capacity in a larger packaging envelope. Similarly, desire for a wide ratio range will generally lead to less efficient CVAD operation and greater waste heat generation.

Orbital Traction developed models for a matrix of CVT geometries to be considered for the proposed CVAD. The geometries were first optimized for the best efficiency at the minimum and maximum ratio range required for this application. These geometries were then scaled from the smallest possible to the largest chosen diameter for this application. The conclusion was the larger diameter unit with the minimum required ratio range provided the best efficiency and longest predicted life. A final geometry was developed based on a commercially available planet size that was closest to the optimized variant.

Cooling requirements for the system were then calculated following the determination of the device geometry. Three options were evaluated for removing the waste heat produced. Those options were (1) air cooling a sealed unit; (2) liquid cooling using engine coolant; and (3) a separately mounted oil cooler (radiator). Air cooling proved to be insufficient given the expected underhood temperatures and high ambient temperatures expected in some theaters of operation. Required flow rates and heat transfer surface area for the other two options were calculated, and each was determined to be a viable means of cooling the CVAD.

Engine Torsionals

In order to mitigate the effect of torsional oscillations on devices attached to engine crankshaft, automotive designers often use torsional dampers. As part of the Phase I research, Orbital Traction developed an engine system model that was used to specify the damper required for this particular application.

In this application, the torsional damper must meet two criteria.

1. The torsional compliance of the damper must be such that it lowers the natural frequency of the combined system to a level below any frequency that could be excited by the engine.
2. The torsional displacement of the damper must be sufficiently large to allow for the transmission of the full range of drive torque to the alternator across the full range of engine speeds while taking into account the change in the effective driven inertia as the CVAD changes ratio and controls alternator input speed.

The model developed as part of the Phase I effort was used to determine the necessary damper characteristics (spring rate and damping coefficient) needed to lower the natural frequency of the combined system below the frequency of the engine torque pulsations.

A free body diagram of the engine / CVT / alternator system was created, and a system dynamic model was developed using Matlab Simulink. A schematic of the Simulink model is shown in Figure 5.

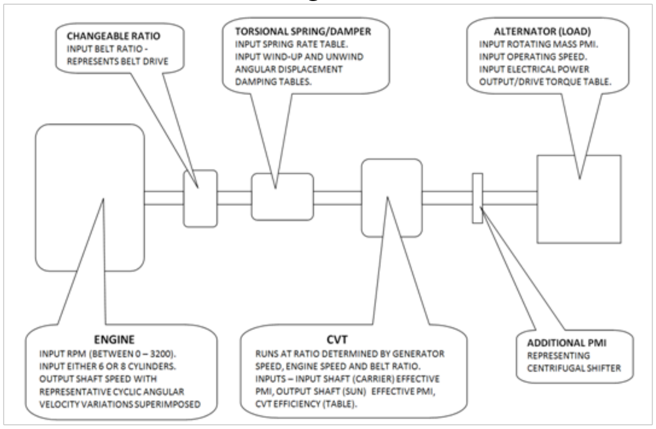

Figure 5: System dynamic model for torque pulse simulation.

Using the System Dynamic Model, a 96 trial design of experiments (DoE) was run to determine which combination of spring rates and damping coefficients provided acceptable overall system performance. The DoE included maximum and minimum alternator electrical loading and was conducted at six engine speeds ranging from the 700 rpm idle through to 3200 rpm.

The simulation of the complete dynamic system provided the stiffness and damping rate required to achieve the necessary level of damping.

Durability

Durability of the CVAD is of critical importance in any automotive application. The design of the CVAD involves an optimization between device capabilities, packaging and life considerations. In all of these areas, the properties of the materials employed play a major role in the final solution. The mechanical properties of the materials determine the stress levels that the various components of the CVAD can withstand and this directly impacts the torque capacity and power density of the final design. Generally, the highest stresses occur at the point of torque transfer, the area of contact between the planets and the races.

The purpose of the Phase I tribology modeling was to determine whether advanced processing of the standard bearing steels used in the CVAD races would extend the life of the device. As part of these life studies, both near surface and subsurface crack failures were examined.

Under steady state operation of the CVAD, little metal to metal contact occurs. Torque is transmitted through the fully developed oil film that separates the rolling elements. Under these conditions, subsurface crack propagation is the most likely failure mode. During other operating conditions, such as startup and when the unit is operating at the extreme of its rated power, reduced oil film thickness can result in intermittent metal-to-metal contact. Under these conditions, near surface failure modes are expected to dominate.

The stresses seen at the point of contact, known as Hertzian stresses, can lead to fatigue failure of the race material if they exceed certain material dependent thresholds. At the points of contact, the maximum shear stress occurs just below the surface of the material, typically within the first millimeter of depth. When this shear stress produces a resultant tensile stress at the crack tip, these stresses can promote significant crack growth and ultimately lead to failure of the material.

When the level of these stresses during CVAD operation approach the limits of the race materials, fatigue failures may occur in 10’s, 100’s or 1000’s of hours. Starting with a standard alloy bearing steel material as the baseline – 52100 – Orbital Traction investigated the effects of three surface treatments that alter the surface or near surface characteristics of the steel, thereby potentially increasing the durability of the races. The three surface treatments investigated were physical vapor deposition (PVD), high energy beam treatment (HEB), and high intensity peen treatment (HIP).

The models were run at four different Hertzian stress levels, which span the range of expected stress at the points of contact between the planets and the races. These stresses correspond to states of operation from low power to high power transmission by the CVAD.

High intensity peening was determined to have a beneficial impact on predicted CVAD life when compared to the untreated case. However, modeling and Finite Element Analysis (FEA) simulation of both the HEB and PVD treatments resulted in inconclusive results. The FEA models are used to evaluate a boundary value problem at the bearing/race contact interface. This near surface problem is more difficult to solve since the integration formulas tend to become unstable at the surface layer and require additional modeling complexity in order to obtain a solution that converges for the input conditions. It was determined that small changes in boundary conditions created large deviations in simulation results, making any evaluation and interpretation of simulation results questionable. For both the PVD and HEB processes, future experimental testing was deemed to be a superior approach evaluating these treatments.

Orbital Traction’s durability modeling demonstrated that improvements to device life are possible through advanced surface treatments. Experimental studies are ongoing to verify these results and quantify the magnitude of such improvements.

Summary

The Phase I SBIR research resulted in the successful modeling and simulation of a CVAD that can enable an alternator to operate at rated power throughout the entire range of engine speeds. The package size of the proposed CVAD will allow it to fit within the same general diameter as the alternator. Axial length of the CVAD-alternator will increase across the pulley section though, if advantageous for a specific vehicle platform, the CVAD can be mounted adjacent to the alternator. Further, this CVAD is expected to exhibit an acceptable MTBF when maintained as specified. Life predictions for the critical variator components indicate that the maintenance interval or, preferably, mean time between overhauls for the CVAD is not anticipated to be any more stringent than what is normally expected for other components subject to military vehicle engine servicing schedules.

THE TECHNOLOGY

Orbital Traction's CVAD is based on a transmission technology known as the Milner Continuously Variable Transmission. The MCVT is a traction device, meaning it uses "useful" rolling friction (traction) to transmit power through opposing smooth surfaces rather than gears. As with other types of CVTs, it offers step-less shifting over its entire ratio range and increased efficiency over traditional planetary gear transmissions. The infinite number of ratios available across the MCVT's ratio range allows for accurate speed control in many different types of equipment.

At its core, the MCVT consists of a number of planets (balls) rolling between a set of inner and outer races, as illustrated in Figure 8. These planets are constrained within a carrier, which is driven by the rolling action of the planets within the races. While the specific configuration varies by application, generally the outer races do not rotate and are used to set the ratio of the device. The inner races are attached to a rotating shaft. When configured as a speed increaser the carrier rotates, which causes the planets to rotate, which in turn causes the inner races to rotate. The inner races are rotationally coupled to a center shaft. The relative axial position of the outer races determines the ratio between the center shaft speed and the carrier speed.

To change the ratio between the center shaft and the carrier, the outer races of the MCVT move along the axis of the device, either closer together or further apart. The relative position of the outer races of the CVT determines where the planets make contact with the inner and outer races and thus determines the transmission ratio of the CVT.

As a controlled velocity accessory drive, the MCVT sits between the vehicle engine and the accessory being driven. Since the Milner CVT has a continuous ratio range between its upper and lower limits, it allows for the speed of a driven device to be decoupled from the speed of the power source driving the device. Regardless of what speed the power source is rotating, the ratio of the CVT can be adjusted such that the driven device rotates at a controlled, deliberate speed. This could be a constant speed, or in some other controlled manner.

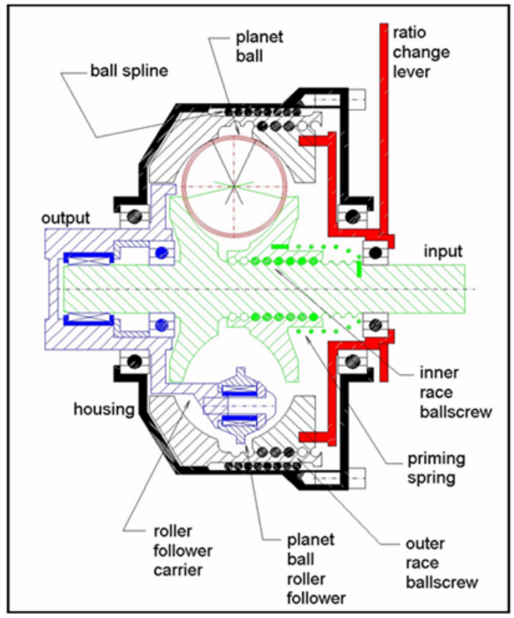

Figure 6: Cross section of Orbital Traction's CVT.

Figure 9 illustrates how Orbital Traction's MCVT can be configured to operate as a CVAD for a heavy duty alternator. The CVT is attached (or integrated into) the alternator and power is supplied to the CVAD at the varying speed of the engine via a belt. The CVAD is controlled such that the output speed to the alternator is maintained within the optimal performance speed band.

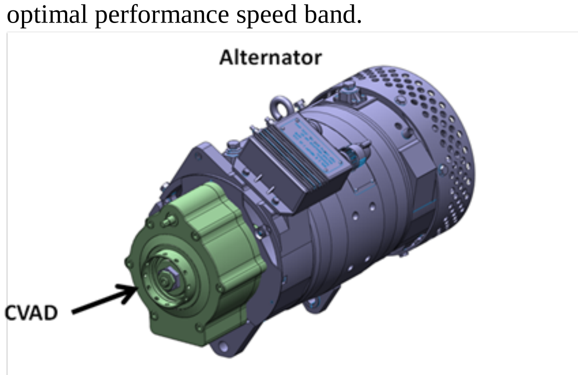

Figure 7: Orbital Traction's CVAD attached to a heavy duty alternator.

OTHER APPLICATIONS

In addition to heavy duty alternators, Orbital Traction's CVAD has potential for other on-board vehicle power generation applications. Specifically, Orbital Traction's CVAD makes possible the generation of synchronous AC power directly from the vehicle engine.

Orbital's CVAD would be placed between the engine and an AC generator. Since the CVAD allows for control of the generator speed independent of the engine speed, the generator speed could be held constant at the synchronous speed of the AC power grid. This AC power could be used for export to other equipment, or could be used in a new vehicle design that utilizes AC power for vehicle systems previously supplied by the standard 24 V DC system.

In addition, several other opportunities exist for improving the performance of other engine accessory drives. Other accessories that would benefit from the ability to operate at either a controlled or constant speed include air conditioning compressors, fuel, water, power steering and oil pumps, and engine turbo- and superchargers, and engine driven cooling fans. In all of these instances, the CVAD would enable for more efficient accessory operation, allowing for improved fuel economy, reduced accessory weight and cost, and enhanced performance.

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[2] US Army RDEC, "On-Board Vehicle Power Briefing & Way Forward", presented at the Joint Service Power Expo, San Diego, April 25, 2007.