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EFFICIENT PTO FAN DRIVE SYSTEM

Brent Marquardt
Michael Brown
Ker-Train Research Inc.
Kingston, Ontario

Mary Goryca
Joe Stempnik
Tomas Pesys
U.S. Army TARDEC
Warren, Michigan

ABSTRACT

Ker-Train Research Inc. (KTR) in collaboration with Southwest Research Institute (SwRI), Control Point Corporation (CPC) and the Tank Automotive Research Development and Engineering Center (TARDEC) Ground Vehicle Power and Mobility (GVPM) has completed the design and fabrication of an efficient Bradley Fighting Vehicle (BFV) power take-off (PTO) fan drive system with electronic controls to demonstrate performance gains in top speed and speed on grade as well as provide fuel savings. This paper provides information on the 8-speed fan drive design, technology, and binary logic architecture. The history of the fan drive development is also discussed.

INTRODUCTION

Current ground vehicle cooling systems consume significant engine power to drive the cooling fan and have crude fan drive control units to meet cooling needs. Implementation of efficient drive technology using coplanar gearing, PolyCone clutches and electronic controls has been shown to enhance the operation and efficiency of the cooling fan drive in the Bradley Fighting Vehicle (BFV) improving top speed, slope operation and cooling capability. The advanced drive technology allows for intelligent control of the cooling fan to free up engine power, minimize overheat stressing of the engine as well as maximize fuel savings.

The efficient Power Take-off (PTO) effort is intended to advance both the technology readiness and the manufacturing readiness levels of the efficient PTO fan drive to enable the cooling fan to run at the most efficient speed for the cooling load, thus providing more sprocket horsepower for mobility. In addition, the fan drive will have a “neutral” capability allowing full engine power for short duration dashes as well as improve effectiveness during Advanced Fire Extinguishing System (AFES) events. The drive technology has wide ranging applicability and may be applied in any number of combat or tactical vehicle applications.

Ker-Train Research Inc. (KTR) has been a participant in the efficient PTO fan drive effort for five years. During that time, KTR has delivered multiple efficient PTO fan drive prototypes to the Tank Automotive Research Development and Engineering Center (TARDEC) under prime contractors Southwest Research Institute (SwRI) and Control Point Corporation (CPC) for testing at the component and vehicle level. The efficient PTO fan drive design uses coplanar gear and PolyCone clutch technologies to assemble an extremely compact, multi-speed drive with very high efficiency (90-98%). Electronic controls optimize gear ratio selection and thus fan speed for regulation of power pack temperature.

The efficient PTO fan drive has a targeted 10% increase in efficiency over the baseline unit. In addition, to increase fan drive capability a fan on-off function was incorporated in the design to support fire suppression.

This year the efficient PTO fan drive effort has featured the following:

- Design Iteration and fabrication of four prototype efficient PTO fan drives for M2A4 Bradley vehicle application.
- Testing of the efficient PTO fan drive systems to verify performance.
- Development of vehicle integration and production cost structures of the efficient PTO fan drive system

The efficient PTO fan drive design activities have focused on developing the coplanar gear and PolyCone clutch technologies. Using component level test rigs, gear analysis software and finite element modeling, the components have been optimized to address mobility and fuel efficiency needs of the BFV.

KTR has also participated in test activities at SwRI, Lotus, TARDEC to verify the performance and durability of the efficient PTO fan drive design for future consideration. Long-term durability testing is also being completed under separate TARDEC initiatives.

BENEFITS TO THE WARFIGHTER

The major benefits of this technology are improved vehicle performance and range. The efficient PTO fan drive system uses highly efficient technology to achieve fuel savings and significantly higher Top Speed and Speed on Grade. The efficient PTO fan drive system supports the Warfighter by providing:

- Enhanced platform mobility
    - 8% increase in Top Speed
    - 5% increase in Speed on Grade
- Improved vehicle acceleration with “neutral” capability allowing full engine power for short duration dashes.
- More effectiveness during AFES discharge.
- Greater fuel economy, increasing vehicle range and improved tactical and logistical abilities.
- Additional vehicle cooling to operate under high output power conditions for longer durations

EFFICIENT PTO FAN DRIVE SYSTEM DESIGN

Compact, high efficiency coplanar gear sets are used in the efficient PTO fan drive design. The core hardware is comprised of gear and clutch modules that interface with a controller to control gear ratios. Lubrication from the BFV transmission provides clutch engagement and also lubricates the gears and bearings. External lubrication lines are run between the PTO casting lubrication port and the valve manifolds. A wiring harness provides power and electrical signals to and from sensors and valves at each drive relative to the controller. The efficient PTO fan drive housing was designed to include proportional pressure control valve port and oil flow passages to feed the clutches and engage the on-off clutch.

The efficient PTO fan drive design iteration in the last year has concentrated on improvements to the overall ratio spread for a reduction in space claim, weight and parasitic engine power jumps between ratios.

The overall design features of the efficient PTO fan drive include:

- Binary logic transmission (BLT) architecture that consists of 8-speeds with similar power steps between gears.
- Coplanar gear sets that have high contact ratio and power density.
- PolyCone clutches that have low parasitic drag, high torque capacity and compact packaging.
- One-to-one eccentric torque couplings used in conjunction with coplanar gearing.
- Gear ratios to optimize cooling system effectiveness
- Power capacity up to 150hp driving the cooling fan
- Significant reduction of heat rejection into the system
- Electronic Control System
- Interface with the existing baseline PTO components and the HMPT transmission

EFFICIENT PTO FAN DRIVE TECHNOLOGY

The efficient PTO fan drive system incorporates the following three key technologies:

- Binary logic transmission (BLT) architecture
- Coplanar gearing with one-to-one eccentric couplings
- PolyCone clutches

The combination of these advanced system technologies and the corresponding product hardware give the fan drive significant improvements in physical design, operating performance, system efficiency, and automotive propulsion capability when compared to the existing variable fill-fluid coupling fan drive.

The BLT technology can be applied to almost any power delivery system that uses a gearbox or an equivalent mechanism. The technology can be easily adapted to bicycles, passenger cars, trucks, military equipment, accessory drives, industrial machinery, and many other applications. As an analogy, consider five light bulbs with wattage in the geometric progression 1, 2, 4, 8, and 16 Watts and separate on/off switches. As switching takes place in all on/off combinations for the five bulbs, a light spectrum with 32 intensities will result, beginning at 0 W when all switches are “off” and ending at 31 W when all switches are “on.” BLT adapts binary system logic to a mechanical transmission. Thus, an interconnected series of five gear sets, with ratios in the same progression as the light bulbs, will provide a transmission with 32 ratio states. Automatic transmission development has been a gradual evolution of old techniques. Binary Logic technology is revolutionary; so much so, the torque converter can be completely eliminated.

COPLANAR ADDENDUM CONTACT GEARING

Coplanar gearing utilizes a unique patented gear tooth form called the “addendum contact” since contact is made at the pitch point and progresses towards the tip of the gear tooth as it passes through the gear mesh. This gear tooth form is designed to provide extremely high contact ratios when compared to conventional gearing. This high contact ratio allows for more torque to be transferred and the overall gear set module to be very compact. Figure 1 displays the high contact ratio achieved in one of the 8-speed gear set meshes.

Figure 1 - Addendum Contact Gear Mesh

Advantages of coplanar gear sets include:

- High contact ratio (> 4 teeth) providing high capacity & quiet operation
- Wide ratio range
- Error-proof assembly, and
- Configurations using a single gear mesh and a one-to-one eccentric torque coupling that can achieve very small ratio changes on a single axis.

The result is superior efficiency, capacity and compactness over other fan drives using conventional gear-trains.

POLYCONE CLUTCHES

PolyCone clutches use a unique cone profile to increase torque carrying capability in a smaller envelope, as shown in Figure 2. The wedging action in a cone clutch increases the normal force on the mating cone. The tangential friction force and the torque capacity are thereby increased, thus fewer plates can be used to carry the same amount of torque.

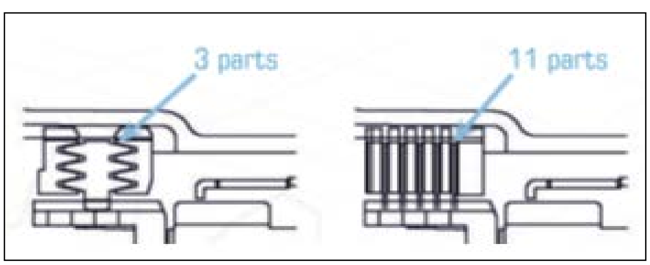

Figure 2 - PolyCone Clutch Packaging

PolyCone clutches provide a significant reduction in parasitic losses, which not only improve efficiency, but also reduce cooling demand. As shown in Figure 3, parasitic losses are greatly reduced when the clutch elements are separated in a disengaged state. With PolyCone clutches, the number of clutch elements is reduced by a factor of three, which also improves reliability through fewer components. A typical PolyCone clutch pack assembly is shown in Figure 4.

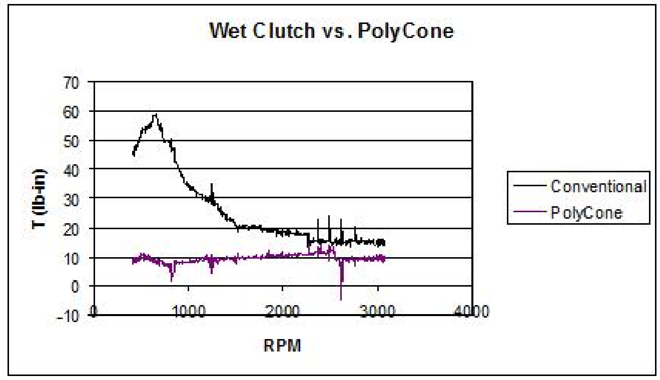

Figure 3 - Wet Clutch vs. PolyCone Drag

Figure 4 - PolyCone Clutch Pack Assembly

BINARY LOGIC ARCHITECTURE

For this application, binary system logic is adapted to an 8-speed mechanical transmission. An interconnected series of three gear sets, each of which can be “on” or “off” in binary fashion (“off” implies a 1:1 ratio), provide a transmission with 8 speeds of similar step size (Table 1) and a ratio spread of 1.575:1 to 1:1.

Table 1 - Efficient Fan Drive Ratios

Module Ratios					
Gear	**X^1**	**X^2**	**X^4**	**Ratio**	**1/Ratio**
1	0.941	0.882	0.765	0.635	1.575
2	1	0.882	0.765	0.675	1.482
3	0.941	1	0.765	0.720	1.389
4	1	1	0.765	0.765	1.308
5	0.941	0.882	1	0.830	1.204
6	1	0.882	1	0.882	1.133
7	0.941	1	1	0.941	1.063
8	1	1	1	1.000	1.000

The efficient PTO fan drive is made up of 3 gear set modules that are controlled by binary clutch packs. Each clutch pack has two individual clutches that control the state of the module: in ratio or locked up at 1 to 1. By firing the hydraulic clutch pack, the gear set module produces a gear ratio. When the hydraulic pressure is released, the gear set returns to the 1 to 1 state providing no ratio change. The unique clutch configurations operate without high pressure rotating oil seals and therefore minimize parasitic power losses. The 8-speed assembly also includes an on/off clutch which is used to disconnect the fan drive during engine compartment fire suppression events and can also be used to shut off the fan for power pack warmup in cold environments.

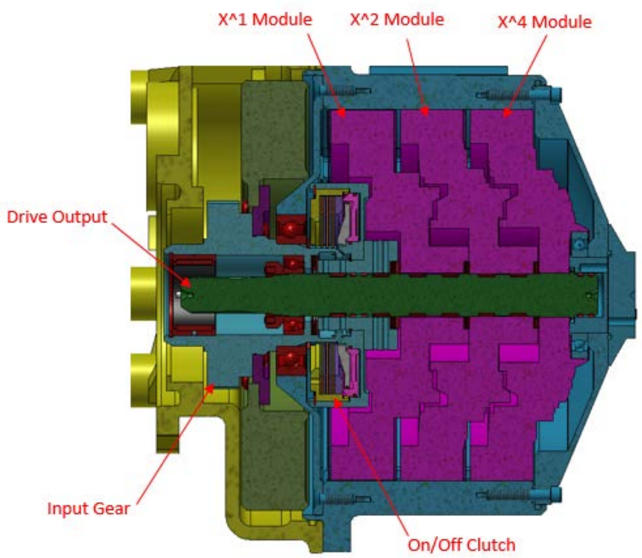

Figure 5 - 8-Speed Cross Section

The ratios selected for the latest 8-speed designs were established from previous Bradley vehicle testing conducted at TARDEC with a prototype efficient PTO fan drive installed. Comparative data was collected from the baseline fluid coupling and compared to the efficient PTO fan drive cooling capabilities. Earlier advanced fan designs covered a wider ratio spread which could provide relatively low fan speeds that were not being used during vehicle testing. The overall ratio spread was tightened to cover the higher fan speeds with smaller steps between ratios. This provided smaller fan speed variations and reduced parasitic engine power jumps between ratios. From vehicle testing, this is the typical area of operation where the most efficient cooling control is needed. The fan drive system also includes two right angled bevel gearboxes (RAGB) which transmit power from the fan drive to the prop shaft which drives the fan. The RAGB ratios can be easily altered and have been used to provide fine adjustment of the maximum fan speeds.

Also, at these high fan speeds and subsequent high fan torques, the production fan drive (fluid coupler) has very high heat rejection levels. Early testing showed large reductions in heat rejection at similar test points when running the efficient PTO fan drive.

HISTORY OF DEVELOPMENT

The efficient PTO fan drive has progressed through multiple phases of development with successful results. TARDEC began the Phase I Efficient PTO fan drive system effort in 2010 and focused on the design, development and demonstration of a highly efficient cooling system drive technology to recapture lost mobility within the same or smaller space-claim for the BFV. The overall goal was to mature the drive technology from TRL 4 (Component or Breadboard Validation in Laboratory Environment) to TRL 7 (System Prototype Demonstration in an Operational Environment). In parallel, a PTO Simulator test rig (Figure 8) was designed and built that is capable of demonstrating operation of the drive. The Simulator test rig includes a 250 hp electric motor, a BFV fan, and allows the operator to vary oil temperatures, flow rates and pressure conditions over the control performance envelope to simulate actual vehicle operating conditions.

TARDEC worked with SwRI and KTR to design, manufacture and test a Phase I prototype unit. The prototype successfully completed spin testing at KTR and was then shipped to SwRI where it underwent functional testing on the simulator test rig. After functional testing the prototype was shipped to TARDEC. As part of the overall program to develop the efficient PTO fan drive system, the prototype unit was installed in a Bradley vehicle and a series of performance tests were conducted in TARDEC's Test Cell 9, Building 212. The goal of the testing was to assess the impact an integrated efficient PTO fan drive had on vehicle performance compared to the baseline production PTO fan drive. The results showed the efficient PTO fan drive improved top speed by 8% and

Speed on Grade by 5% compared to the production PTO fan drive.

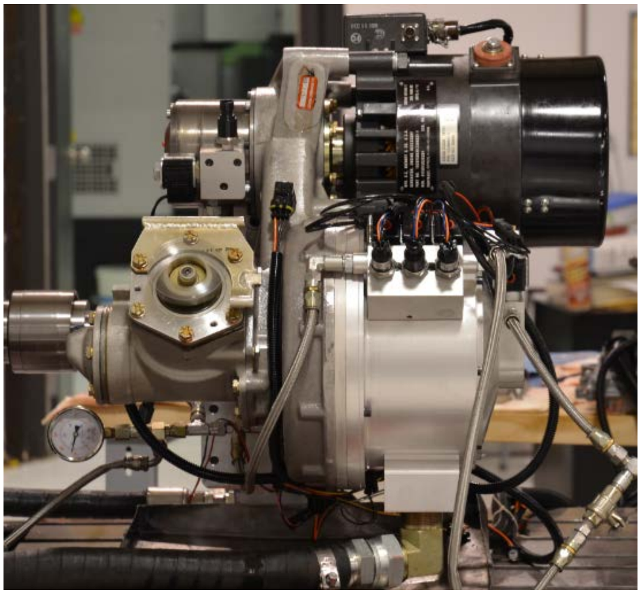

Figure 6 - Phase I Efficient PTO Fan Drive

Phase II of the efficient PTO fan drive development process focused on improving the performance and functional integrity of the design for long-term durability.

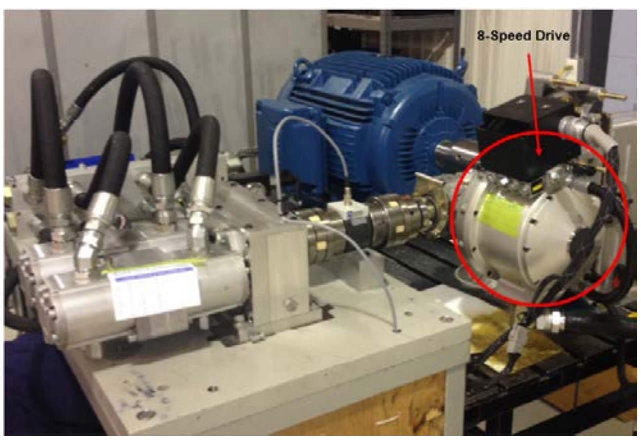

Figure 7 – Efficient PTO Fan Drive Testing at KTR

Phase II included the manufacture and testing of four (4) efficient PTO fan drive systems. Preliminary spin testing was conducted at KTR's facility (see Figure 7) before being delivered to SwRI for further testing. At SwRI, the Phase II test units were put through several Test Readiness Level (TRL) 7 tests including performance, hot & cold storage, shock-vibration and tilt testing. The simulator test rig was used to conduct durability testing of the Phase II efficient PTO fan drive which has successfully accumulated over 300 hours of testing.

Figure 8 – Efficient PTO Fan Drive Testing at SwRI

After extensive testing of both the existing production fan drive and the Phase II efficient PTO fan drive system, further refinement of the ratio spread was deemed to be beneficial. The overall ratio spread in the Phase III efficient PTO fan drive system was reduced to provide finer precision control at the high fan speed and power points.

Phase III of the efficient PTO fan drive system development specifically targeted the BFV A4 variant. This effort includes a design iteration, fabrication and test of four efficient PTO fan drive Systems. Fabrication and assembly of the units are complete. The units are being tested at Ker-Train, SwRI and Lotus Engineering to verify performance, durability, slope climb and performance under various environmental conditions. Software safety checks were completed followed by shift calibration prior to testing. Figure 10 displays the latest generation efficient PTO fan drive system on test at KTR's facility.

In parallel to these efforts, TARDEC initiated an Army ManTech project to improve limited manufacturing capability of the efficient PTO fan drive technology in effort to offer affordable efficient PTO fan drives for Army ground vehicles for fuel savings and improved mobility. This ManTech project is maturing the manufacturing readiness level (MRL) from MRL 4 (Capability to produce the technology in a laboratory environment) to MRL 8 (Pilot line capability demonstrated; Ready to begin Low Rate Initial Production) by developing the fabrication and manufacturing processes to reduce unit cost and increase both reliability and throughput.

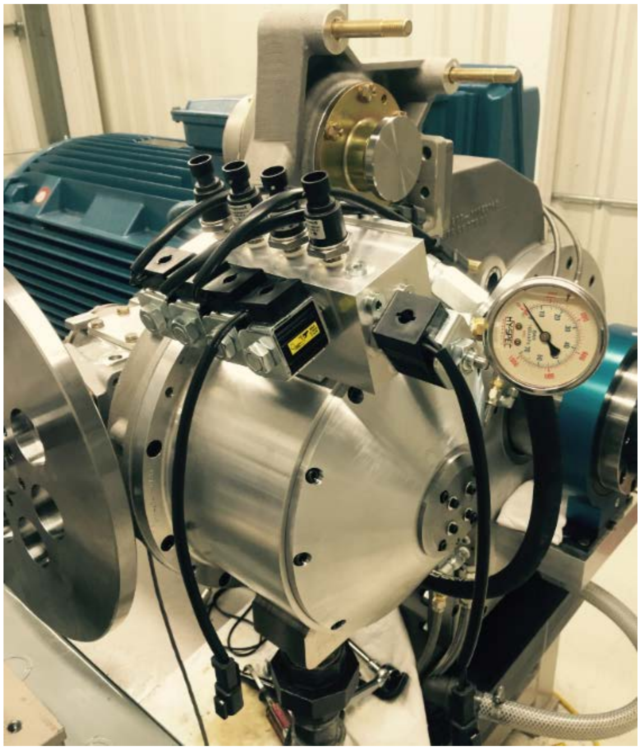

Figure 9 – Phase III Efficient PTO Fan Drive

SOFTWARE, ALGORITHMS & CONTOLLER

TARDEC controls engineers worked with SwRI and KTR to develop a complete control system and extensive testing has been completed over the course of the efficient PTO fan drive system development. An ETAS FlexECU controller interfaces with the advanced drives to control gear ratio. A wiring harness connects the controller to the sensors and directly to hydraulic valve solenoids. PWM proportional pressure reducing valves modulate the clutches. The ability to control the pressure ramp duration and shape during clutch engagement enhances controllability of the clutches. KTR has worked closely to support TARDEC controls engineers with improving and implementing the control code.

SUMMARY

Using advanced drive technology has resulted in significant improvements in operation and efficiency of the cooling fan drive in the Bradley Fighting Vehicle (BFV) improving top speed, slope operation and cooling capability. The coplanar gears and PolyCone clutches met the efficient PTO fan drive goals and were intact at the test conclusion. The advanced drive technology can be considered for efficiency improvements in fan drive applications. Vehicle performance can be improved by minimizing the amount of engine power required to drive the cooling fan system which allows for more engine power to be directed to the output sprocket improving vehicle mobility. The efficient fan drive system can also offer additional cooling capacity over the existing fan drive systems to help sustain the increases in vehicle weight that the BFV is experiencing. In the future, lifecycle cost benefits are also expected with a reduction in operating temperature of the engine and transmission due to the improved cooling capability.

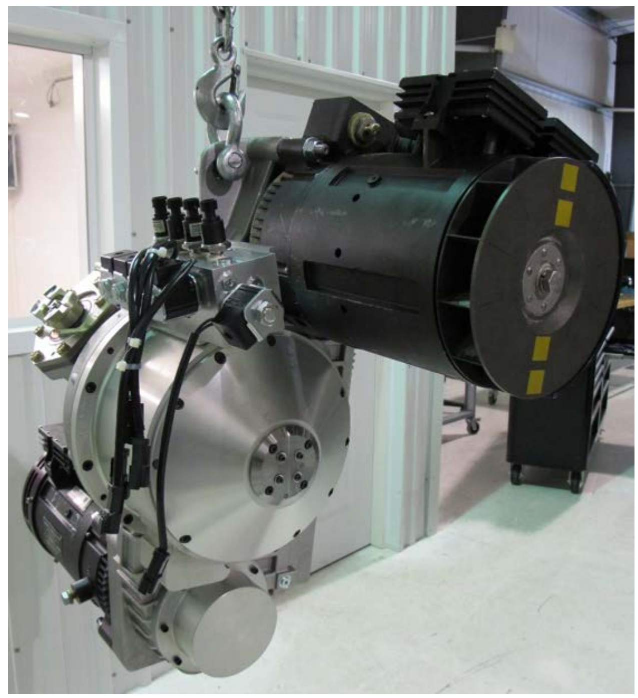

Figure 10 - Efficient PTO Fan Drive

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