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SUPER EFFICIENT POWERSHIFT AND HIGH RATIO SPREAD AUTOMATIC TRANSMISSION FOR THE FUTURE MILITARY VEHICLES

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ABSTRACT

The following paper describes the new SAPA automatic transmissions for the future military vehicles. The very high mobility requirements, the reclaim of weight, power & space and the actual relevance of the fuel consumption require a rethinking and a new vision of the automatic transmission concept and design. This is what SAPA has been working on for the last 12 years obtaining excellent technical and commercial results, a concept aimed at reducing the power losses of the conventional powershifting transmission eliminating the torque converter, reducing the spin losses -due to hydraulic pumps and friction discs-, and improving vehicle mobility on variable terrain situations as off-road.

INTRODUCTION

A new generation of armored vehicles is demanding powerpack concepts with significant improvements in power to weight ratio, fuel consumption and performance as well as maintaining or improving the current reliability of the combat proven systems. SAPA set ourselves this objective ten years ago and conceptualized a whole new family of transmissions in order to provide to the market a reliable and industrial solution but with the required improvements. A concept aimed at reducing the power losses of conventional powershifthing transmission eliminating the torque converter and in the case of tracked vehicles the hydrostatic steering system , reducing the spin losses -due to hydraulic pumps and friction discs-, and improving vehicle mobility on variable terrain situations such as off-road.

The SG850 transmission, as a first product, demonstrated our concept of multi-gear high efficiency powershift transmission. The SG850 transmission was presented at the 2008 NDIA Ground-Automotive Power & Energy Workshop, and has been introduced in different vehicles: Spanish Army Pizarro IFV, Otokar Tulpar IFV and its new version of 48Tm, the SG850-B, will be introduced in a self-propelled howitzer during 2015. The transmission was developed in parallel with the Pizarro vehicle (phase 2) during the years 2004-2009, extensively tested, evaluated and finally validated by the Spanish Army during 2010-2012. The results showed the benefits of the SG850 transmission in terms of performance, maneuverability and cooling demand. The program is in production and the first 20 vehicles will be delivered this year.

Continuing the development of its new technology SAPA started the design of its entire SW (SAPA WHEELS) family of transmissions in 2009. Thanks to its unique and patented multi-gear concept, the transmission exhibits a very high ratio spread of 31 with 24 gears divided in equal steps (geometric progression) of 16% increments. This allows a quasi-continuous variable transmission behavior and as a result an optimization of engine operation. Besides the kinematic concept, the advanced shifting system allows a multi-gear system with a wider overall ratio and narrower steps between gears than a manual automated transmission and without power interruption between gearshifts. These features enable very high mobility in extreme situations (heavy off-road, combat, etc). The transmission, with its planetary gears modules, low drag friction discs and specially developed synchronizer system presents the highest torque/power to weight ratio in the powershift transmissions market. As an example the SW624 transmission is capable of holding up to 3000Nm input torque or 800HP input power, with a sub 490Kg weight. This makes the SW624 the most competitive option for the future 30 to 35 Tm class armored wheeled vehicles, improving its accelerations, speed on grade and reducing its

fuel consumption and, last but not least, cooling demands. Transmission development status is at TRL6 stage and results are showing efficiencies as high as 98%. The next development step is vehicle integration during 2015. This transmission was selected for the US Army TARDEC Topic23 and two units will be delivered during 2014 for in house testing.

In order to meet future vehicle demands and Topic 23 requirements the transmission can be equipped with a modular hybrid kit providing 150kW continuous power, developed also at SAPA. Additionally, the modular concept and the kinematic system with high degree of commonality permit more cost effective options for other less demanding military applications or for the civil market.

PROVEN TECHNOLOGY. THE 32 SPEEDS SG 850

In the year 2004 SAPA started the development of the first Powershift Automatic transmission without torque converter for a tracked vehicle, as well as replacing the Hydrostatic Steering system with a high and accurate response mechanical and continuous ratio like system. This transmission completed more than 2000 hours on the test bench and more than 20000Km in vehicle tests before being selected by the Spanish Army for their new vehicle PIZARRO phase two.

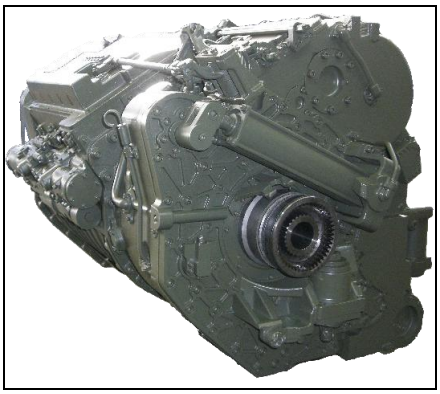

Figure 1. SG 850 Transmission

The SG850 transmission demonstrated the high efficiency of the concept and the performance improvements. The following set of figures show the efficiency results measured on the test bench for gears 17, 21, 24, 28 and 32. Efficiency is measured throughout the complete input speed range for input loads of 25%, 50%, 75% and 100%

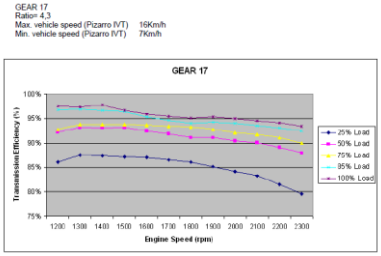

Figure 2.1. SG850 Efficiency Gear 17

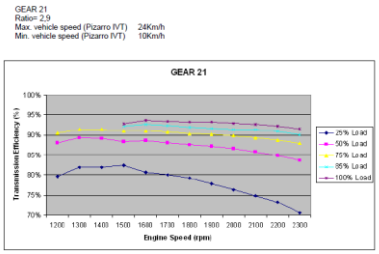

Figure 2.2. SG850 Efficiency Gear 21

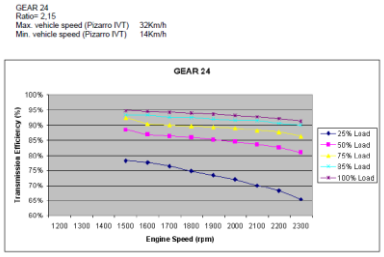

Figure 2.3 SG850 Efficiency Gear 24

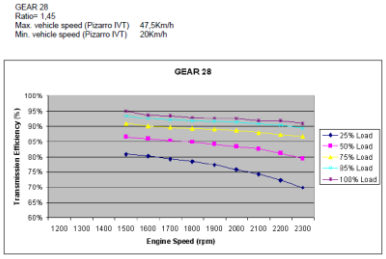

Figure 2.4 SG850 Efficiency Gear 28

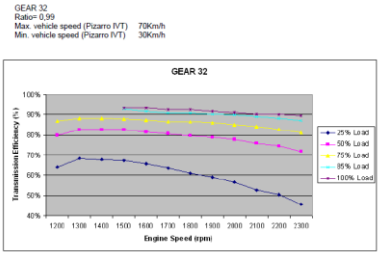

Figure 2.5 SG850 Efficiency Gear 32

These results can be summarized as follows:

- Lowest efficiency is in 32nd ratio at 2300rpm engine speed with 720hp input power is 89,59%. The extrapolation to 850hp input power will imply a lowest efficiency of 90%.
- Lowest efficiency in the optimum fuel consumption range (1500rpm engine speed) and 100% load is 93%
- Lowest efficiency in the optimum fuel consumption range (1500rpm engine speed) and 75% load is 88%

The efficiency performance of the SG850 transmission is very constant throughout the engine speed range: The efficiency drop from gear 17 to 32 is only 4%. This implies a stable heat rejection and simplifies the cooling system. The transmission power loss varies from 40kW to 53kW. In a transmission using a torque converter this range could vary from 53kW to 130kW.

In vehicle tests were performed at the Spanish Army test track in Sevilla. Performance tests, durability and reliability tests, and comparative tests with a Pizarro phase 1 with a conventional transmission were performed.

Figure 3. Spanish Army in vehicle tests

As an example of SG850 transmission improvements an acceleration run from stand still to 60km/h was performed with both vehicles. As can be seen in the next figures the SG850 transmission showed improvements from 15 to 25% depending on the speed range.

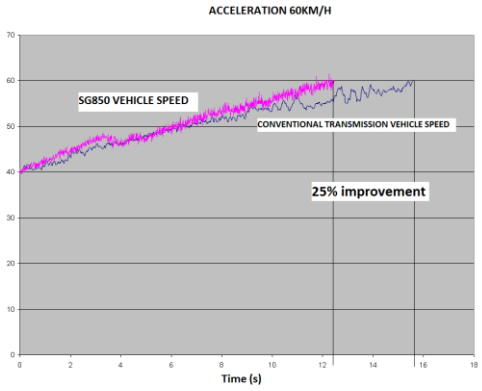

Figure 4. Accelerations

SG850 transmission Steering system

The pure mechanical steering system, due to its high efficiency, provides the required maneuverability for a combat vehicle in terms of turn radii, pivoting speed, (neutral pivot is also possible) on a very compact and reliable system.

Besides that, thanks to its unique concept of a continuous ratio change mechanical system, the vehicle steers, as reported by several drivers, like a passenger car. Easy to control, without requiring large forces on the steering wheel, excellent control at high speed and with minimal decelerations during turns.

Figures 5 (5.1 and 5.2) show the comparison between a vehicle with a hydrostatic steering system and the SG850 transmission in order to show the response of the system and the vehicle speed reduction with both systems. The maneuver consists of a 180º turn at maximum steering wheel while maintaining the position of the accelerator constant during the turn. The first figure 5.1 shows how the speed of the vehicle with the hydrostatic system drops heavily, first because of the poor efficiency of the hydrostatic system and second because of the open condition of the torque converter due to the first speed drop of the engine. In the second figure the vehicle with SG850 transmission maintains the speed. We should take into account that a maneuver like this request 200kW. If the efficiency of the system is as low as 60% , as it in the case of a hydrostatic system the engine power needed will be 200/0,6=333kW and that represents the 75% of the total engine power, only for steering the vehicle. This sudden increase of engine power demand will start a sequence of downshifts in an open torque converter condition, therefore lowering even more the overall efficiency and finally if the drivers maintains the steering maneuver the vehicle ends on a neutral turn, turning the vehicle at 0km/h speed. In the case of the SG850 mechanical system , with 91% efficiency, the engine power need will be 220kW. The engine and the vehicle will maintain the speed and radius of turn constant as long as the driver wants, similar to a passenger car. If the driver releases the accelerator the vehicle will slow down and the vehicle finally will perform a neutral turn if the driver continues turning the steering wheel, a maneuver desired in some situations.

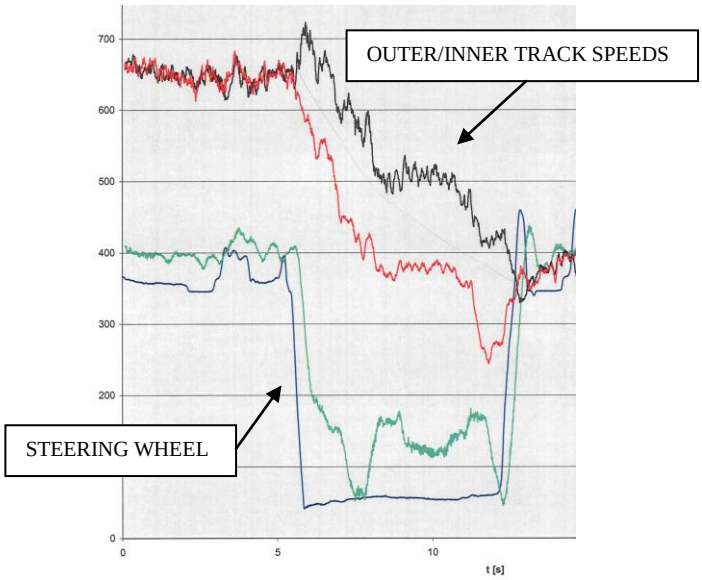

Figure 5.1. Transmission with hydrostatic steering

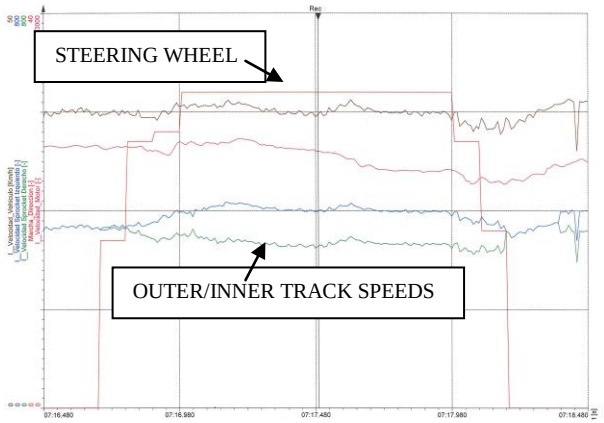

Figure 5.2. SG850 transmission

Another important feature of the concept is the possibility of dead engine steerability in normal operating mode without any additional signal or torque converter aggressive lock-up mode that implies reliability problems. The introduction of electronic engines in military tracked vehicles has led to a number of new situations where the engine of the vehicle can be shut down: electronic accelerator problems, sensors signals problems, ECU failure, etc. Therefore the engine could be shut down during an open mode torque converter turning maneuver if one of those problems occur and as a consequence loss the vehicle driveability or steerability, or on the other hand, if an emergency torque converter lock-up mode is activated the lock-up clutch will be engaged at a high speed difference and will be used out of its design specs and thus will cause reliability problems as reported on several occasions by the users

The SG850 transmission, thanks to the elimination of the torque converter, maintains always the bidirectional power capability and therefore avoids dead engine loss in steering situations, provides full engine brake capacity and towing start capability in the normal mode, simplifying the operation.

THE SAPA WHEELS FAMILY 16-24 SPEEDS

Thanks to the excellent results achieved with the SG850 transmission SAPA decided to start the development of the wheels vehicles family. The main goal was again to overcome the inefficiencies of the conventional transmission but providing a cost competitive transmission to a more demanding market, in terms of cost, than the crossdrive transmissions. The objective was a high efficiency powershifting transmission concept without torque converter, an alternative to the actual 6 and 7 speeds automatic transmissions. Commonality between the different transmissions of the SAPA family was a requirement and efficiency with an optimum cost was the challenge. As it is explained later improvements in the shifting strategy were also introduced.

The SW kinematic concept, a double combination of two planetary P1 and P2 gear modules plus a start up clutch, provides 16 ratios with a 16% step between them in a geometric progression. The transmission, therefore, behaves like a CVT as can been seen in the following traction curves diagram.

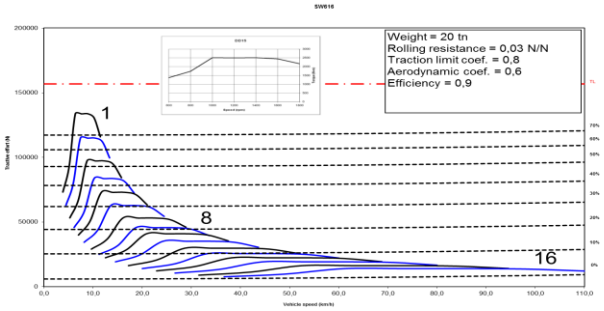

Figure 6. 16- speed traction curves and ratios

This results in an optimization of the engine that could go even further by benefiting the design and/or concept of the engine thus allowing more efficient and reliable concepts. Results demonstrate improvements of 15% to 25% in terms

of performance and 20% to 30% in terms of fuel consumption.

Furthermore, adding a new planetary, equal to the one of the P2 module, a 24 ratios transmission is obtained.

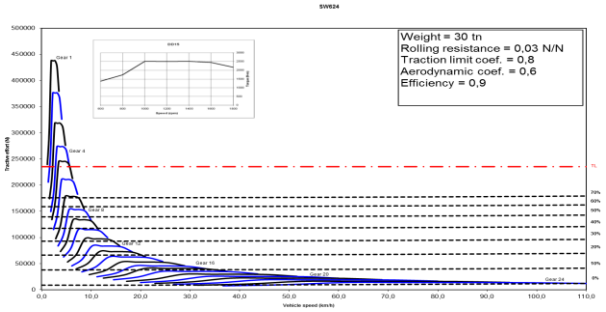

Figure7. 24- speed traction curves and ratios

With this kinematic concept the first step in order to achive the goal was established. A multi-gear transmission with powershifting capability and industrially competitive.

SW design

After this, a design solution was needed. In order to overcome the cost issue, cost effective solutions for the clutch modules were designed optimizing them via FEM and CFA and thus reducing the number of discs. Thanks to that, the use of separating springs was avoided, in consequence simplifying the design and lowering the cost but maintaining a low drag clutch modules.

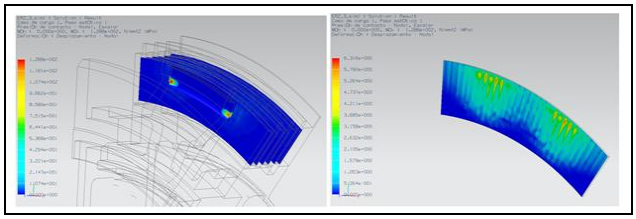

Figure 8. Clutch pressure distribution calculation results

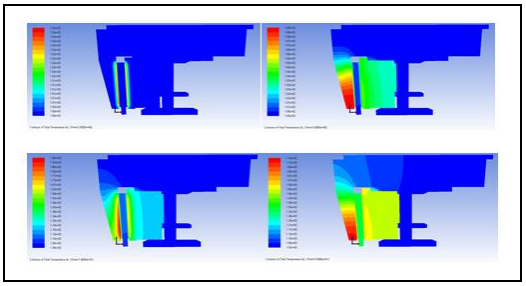

Figure 9. Clutch thermal analysis results

Besides, smart solutions for the centrifugal equalization chambers were also provided.

Figure 10. Two clutches with single Chamber

A common central shaft with four clutch oil passages was the challenge for the manufacturing department but with it, the compactness and low drag piston rings requirements were achieved.

Figure 11. SW616 and SW 624 central shaft

For the Planetary modules an assessment between helical or spur gears was done. Using a four square test rig both solutions were evaluated showing that the best efficiency and the highest power to weight ratio was the for the spur concept. Furthermore, the kinematic concept avoids idling gears thus the NVH issues are reduced comparing to the conventional transmissions kinematic concept

Powershifting

The SW kinematic concept provides an automatic transmission with 8 clutch to clutch shifts, 4 double clutch to clutch shifts and 3 shifts with multiple clutches shifting.

Therefore, 8 powershifts with an “start of the art” shifting control is achieved, plus SAPA developed a new powershifting control for the 4 double clutch to clutch during the SG850 transmission development and for the new SW an improvement adding a new speed sensor will be

implemented in order to shorten the time of shifting and improving the shift quality, which needs to be done for a wheel vehicle transmission.

In summary, 12 of 15 shifts (16 speeds) are direct powershifts. This is the status of the SG850 transmission and as can be seen in the next figure 3 shifts are performed as multiple clutch shift. The current results show excellent performance compared to competitors, with less than 8 seconds acceleration form 0 to 32km/h and less than 24 seconds from 0 to 60km/h.

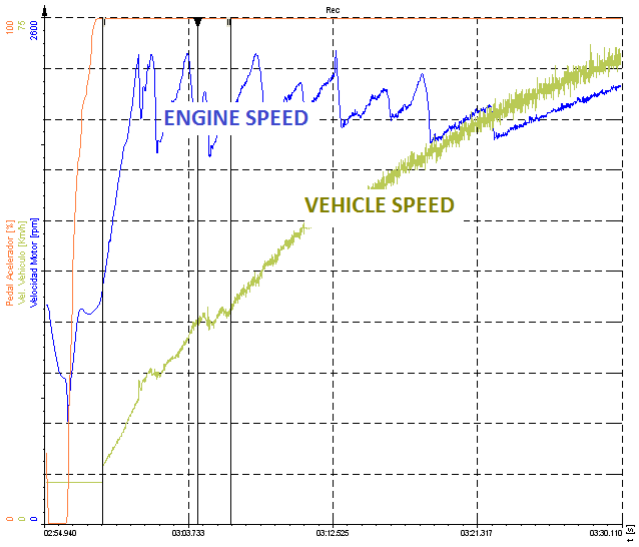

Figure 12. SG850 transmission acceleration

In order to improve the efficiency of the transmission and being cost competitive a dog clutch system was introduced for one of these 3 shifts, therefore the transmission is more compact, has lees weight and reduces the cost. But the time of shifting increases for this shift. In order to solve this problem a new system was added to the transmission to perform as a powershift.

The result is an automatic power shift transmission with very high efficiency and cost competitive.

SW 600

The first range of transmissions developed is the SW600 (SW 616 and SW 624). The SW624 transmission is capable of holding up to 3000Nm input torque or 800HP input power with its less than 500kg weight. This makes the SW624 the most competitive option for the future 30 to 35 Tm class armored wheeled vehicles, improving its accelerations, speed on grade and reducing its fuel consumption and, last but not least, cooling demands. This transmission was selected/awarded by the US ARMY for its development program Topic 23 (Efficient powertrain technologies). The SW616 transmission with the same input torque and power capability is a very compact option for the 20Tm range armored vehicles, or for more heavy armored vehicles with two ratios transfer case or for heavy off road trucks.

Figure 13. SW 624 on the test bench

Efficiency

The main SW design objective is to improve the efficiency of the system. As explained before the quasi CVT concept allows the engine optimization and the elimination of the torque converter and the mechanical concept of the transmission provide efficiencies of the SW transmission always and in any condition better than 90% at full load.

In the next figures 14. the results for the SW600 range are presented

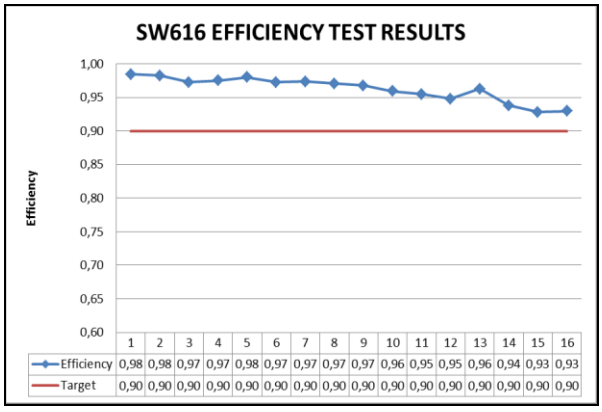

Figure 14.1. SW 616 Efficiency

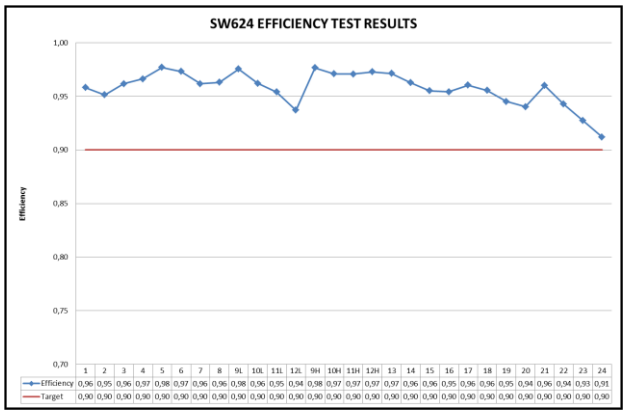

Figure 14.2. SW 624 Efficiency

CONCLUSSION

This paper describes a new technology concept for heavy vehicle automatic transmissions that has been developed with the aim of overcoming the faults of the 'old' torque converter systems in terms of efficiency, heat rejection and power/weight ratio. These characteristics have been significantly improved with respect to those systems.

These improvements allow vehicle manufacturers to deliver better products to their customers, with extended range, lower operating costs, simplified logistics, lower powerpack volume, higher mobility, better reliability and less sensitivity to hot weather.

The product has achieved TRL8 and is currently being delivered to final users for entry into service.