First Driving Test Results of FEV's 7H-AMT Hybrid Transmission

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Summary and Outlook

In this article first vehicle test results of FEV's new 7H-AMT have been presented and discussed. After an introduction of the transmission concept, shift procedures for combustion engine and electric motor shifts were discussed. FEV's shift quality assessment tool FEVos was used to evaluate the shift quality of the prototype vehicle in an objective way. It was found that the principle of electric torque support during AMT shifts is working very well as long as combustion engine power and electric motor peak power are properly balanced. A typical configuration for a small to medium sized full hybrid vehicle with an 80 kW combustion engine and 50 kW electric peak power would lead to a new shift quality benchmark in this vehicle class for a large part of the operating envelope at very low transmission prices. The projections for shift quality at high accelerator pedal positions can be confirmed after the vehicle has been fitted with an improved electric drive system in late 2011. Fuel consumption in NEDC was reduced by 31% compared to the base vehicle with manual transmission, achieved by combustion engine downsizing and the integration of 7H-AMT. For future investigations with a mass production transmission torque sensor this type of device has been integrated in the transmission. The sensor will be used to improve shift quality, performance and robustness.

Technical Overview

The main idea behind 7H-AMT is to provide an efficient and cost effective transmission solution for hybrid powertrains. Especially for full- or plug-in-hybrid powertrains, the installed electric power is significant and can be used to take AMT shift quality to a new level. The transmission concept has been presented in [1] and is characterized by two main features:

- Provide electric torque support for all combustion engine gearshifts for vastly improved shift quality compared to conventional AMTs
- Create 11 forward gears with only 4 synchronizer units: 8 for the combustion engine (ICE), 7 of which are progressively stepped and well usable, and 3 for the electric motor (EM)

The key to these features is the gearset layout with its unique arrangement of the four synchronizer units. Fig. 1 shows the layout and the ratio stepping of the prototype transmission. As long as one of the idler gears next to synchronizer unit C on the output-shaft is not engaged, this gear can be used to transfer torque from the first input shaft to the second input shaft. Thereby, existing gear ratios are multiplied to "generate" new gears. The gears 1, 3, 7 and R are such "generated gears", where three gear pairs in a row are used to create the total ratio. In order to provide electric torque support, the layout provides two independent torque paths to the wheels. During gear shifts, one of the two paths always remains active. During combustion engine gear shifts, the electric motor can fill up the torque gap that would usually occur for AMTs. During all

EM shifts, the combustion engine continues to drive the vehicle.

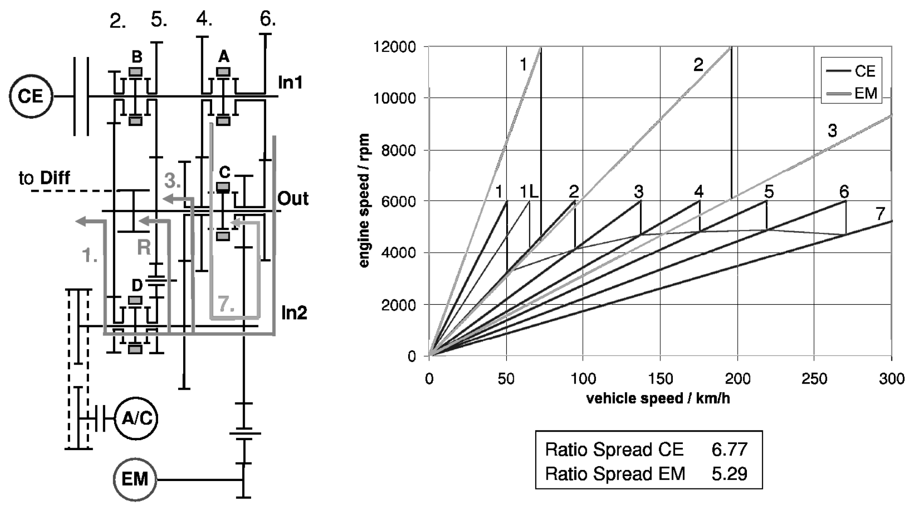
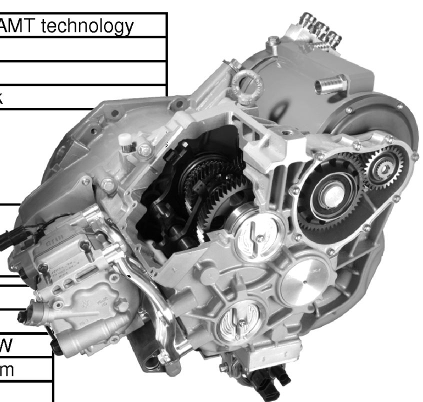


Fig. 1: Gear arrangement and ratio stepping of 7H-AMT

Type	3-shaft parallel hybrid transmission, based on AMT technology
Installation	Transversal, FWD, installation length 356 mm
Clutch	Single dry, normally closed
Actuation	On-demand electro-hydraulics with power pack
Hybrid functions	- Start/Stop - Regeneration - Boost - All electric driving
Special functions	- Electric torque support - Electric drive of A/C compressor during stop phases

Input CE	Number of gears (forward / reverse)	7+1L / 2	-
	Ratio spread	6.77	-
	Power	160	kW
	Torque	320	Nm
Input EM	Number of gears (forward / reverse)	3 / 1	-
	Ratio spread	5.29	-
	Power (permanent / peak)	36 / 70	kW
	Torque (permanent / peak)	70 / 140	Nm
	Maximum speed	12000	rpm



7H-AMT prototype transmission

Table 1: Technical overview of 7H-AMT prototype contains a technical overview of the prototype transmission and the performance numbers of the combustion engine and electric motor for which it has been designed.

7H-AMT Powershifts

Fig. 2 shows a measurement of a powered 1-2 upshift as an example for combustion engine shifts with 7H-AMT. Such a shift can roughly be divided in three phases. In the first phase the torque is handed over from the combustion engine to the electric motor. For the short time span of one second the electric motor can provide up to two times its nominal steady state power. When the clutch has completely opened the shift fork of first gear is disengaged and second gear is engaged.

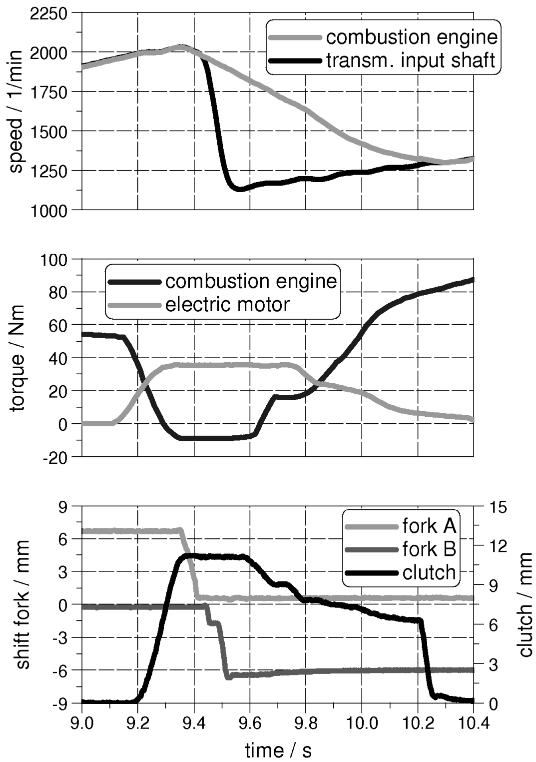


Fig. 2: Combustion engine shift with 7H-AMT

Because the gearset layout offers very low inertias to be synchronized, the synchronizer engagement time is 30 ms only which leads to a total shift fork movement time of 200 ms. In the third phase of this 1-2 ICE shift the torque is handed over to the combustion engine again by closing the clutch and decreasing the electric motor torque. This is done by model based feedback control of engine speed by regulating clutch torque and ICE torque to realize smooth speed adaption of the combustion engine [3]. The total shift time from opening the clutch until reaching target engine torque in next gear is one second in this example.

The gearset layout of 7H-AMT allows to operate the electric motor in three different gears. Fig. 3 shows a 2-3 upshift of the electric motor. During the shift the vehicle is solely driven by the combustion engine. The shift directly begins with the movement of the active synchronizer unit in the electric motor path to neutral. The following speed control of the electric motor to the target speed of the next gear is done by operating the electric motor in generator mode. Limiting factor in this phase is the maximum available generator torque. In the last phase of this shift type the new gear is synchronized in 20 ms only which is possible because of the active speed control of the electric motor.

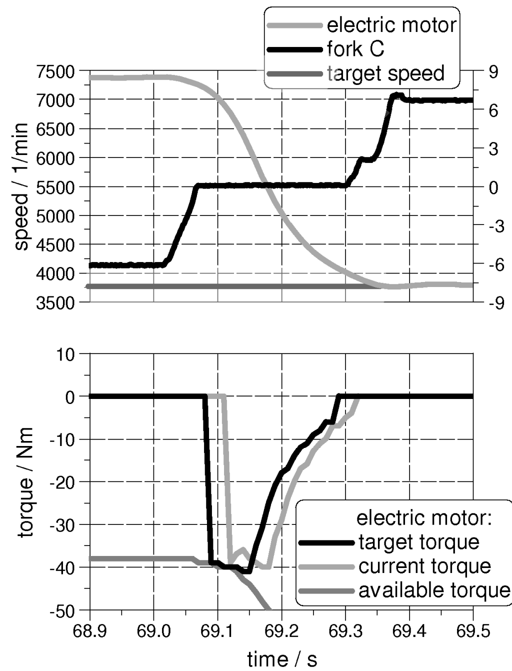


Fig. 3: Electric motor shift with 7H-AMT

Shift Quality Assessment

Shift quality is one major attribute of all automatic transmissions. Therefore a deep investigation of 7H-AMT's shift quality has been performed to evaluate this concept. Special attention has been paid the function of electric torque support. To do this evaluation in an objective way, FEV's objective shift quality tool "FEVos" was used. FEVos uses two characteristic numbers to evaluate the shift quality based on the measured longitudinal acceleration of the vehicle. The VDV (Vibration Dose Value) is basically an integration of the fourth power of a bandpass-filtered acceleration signal over the shift event [2]:

$$VDV = \left[\int_{t=0}^{t=T} a^4(t)dt \right]^{1/4}$$

This number is an objective value for the shift shock in a frequency range, where human beings are very sensitive against vibrations (1-30 Hz). Lower frequency acceleration changes are evaluated by the LFP (Low Frequency Percentage) value

$$LFP = \frac{(a_{max} - a_{min})^{1/4}}{a_{max}^{0.5}} \cdot 100\%$$

with a_{max} being the acceleration level before the shift and a_{min} being the minimum acceleration level during the shift. The LFP represents the low frequency change of acceleration during shifts, e.g. the torque gap of AMT shifts. With VDV and LFP, the characteristics and quality of a shift can be described almost completely. FEV has collected data from different vehicle applications, different transmissions and different transmission types to objectively compare measured shift quality in FEV scatterbands.

Currently, only limited power is available at higher speeds of the prototype electric motor inside the 7H-AMT demonstrator vehicle. Therefore, only measurements of electric torque support up to 40% accelerator pedal were available for evaluation in this article. Values for VDV and LFP above 40% are based on simulations and predictions.

Fig. 4 shows the VDV- and LFP data measured on the 7H-AMT prototype vehicle in the scatterband of typical automatic transmissions (AT, DCT, AMT) for a powered 1-2 upshift. Here, the VDV value as an objective value for high frequency shift shock is within the scatterband of ATs and DCTs for low pedal positions and at the low end of AMT scatterbands for higher pedal values. Taking into account the early calibration status of the prototype vehicle, it is safe to assume that in a series development process, the VDV will achieve the quality of ATs and DCTs. Key factor will be the improvement of clutch and electric motor control as well as shift procedures (all of which currently have prototype status). In contrast to conventional AMTs, there is no inherent trade-off between VDV and LFP. Both values can be optimized almost independently from each other.

More interesting for the evaluation of the 7H-AMT concept is the LFP value because this value is an objective measure for the effectiveness of the electric torque. The measured LFP values for the demonstrator with deactivated electric torque support show the typical AMT characteristics completely within the AMT scatterband.

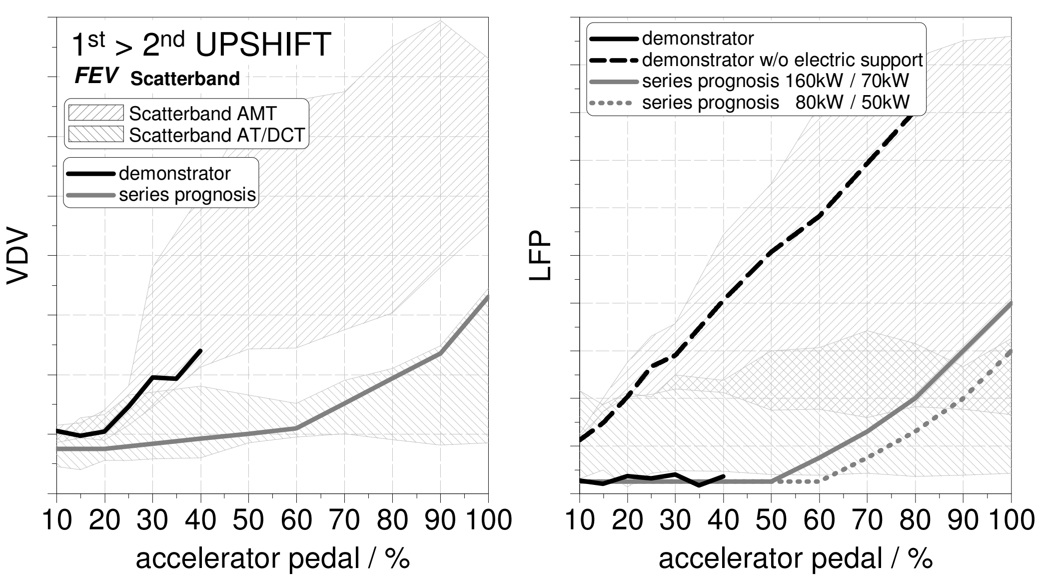


Fig. 4: Shift quality of combustion engine shifts in FEV scatterband.

For the measured range of accelerator pedal positions up to 40% the behavior of 7H-AMT with electric torque support is at the lower end of the

AT and DCT scatterband thus confirming the concept of this transmission for the case of properly balanced electric power compared to the power of the combustion engine.

Due to the boundary conditions of the research project, 160 kW of combustion engine power but only 70 kW electric peak power are available in the demonstrator vehicle. This leads to decreasing shift quality at higher pedal positions (shown by an increasing LFP value). Fig. 4 also shows predictions for the LFP values based on simulations for a more favorable power ratio. For a power ratio of 80 kW (ICE) to 50 kW (EM peak), the expected LFP values lie completely within the AT / DCT scatterband up to 100% accelerator pedal position. Up to 60%, shift quality is at the lower end of the LFP scatterband. This ratio of 80 kW to 50 kW (peak) represents a typical powertrain for small and medium full hybrid vehicles. For this kind of vehicle, 7H-AMT is a cost effective and efficient transmission solution with excellent shift quality.

Fuel Efficiency Improvement

The most important motivation for research projects on hybrid powertrains is the potential for fuel efficiency improvement compared to conventional powertrains.

functions for each operating mode. During driving, the strategy compares the cost of all modes and decides which mode to operate in under consideration of efficiency, driveability and hardware limitations. The goal of the hybrid strategy is to keep the battery on an adequate energy level, so called “Charge-Sustaining-Strategy” [3].

To evaluate the efficiency improvement of the “Europa-Hybrid” vehicle, several chassis roller test bench investigations were conducted. Fig. 5 shows measured values from an exemplary NEDC cycle. For the low speed parts of the cycle the hybrid strategy chooses pure electric driving as the optimum whereas the remaining part of the NEDC cycle is mainly driven in parallel mode. In this mode, the hybrid strategy operates the combustion engine at higher loads to recharge the battery to enable pure electric driving later on. The measured overall fuel consumption reduction compared to the Ford Focus ST base vehicle (as measured at FEV) is 31% in NEDC down to 7.0 l/100 km. This improvement includes downsizing the combustion engine from 2.5 to 1.8 liters displacement (torque and power kept constant) and a replacement of the stock 6-speed manual transmission with 7H-AMT.

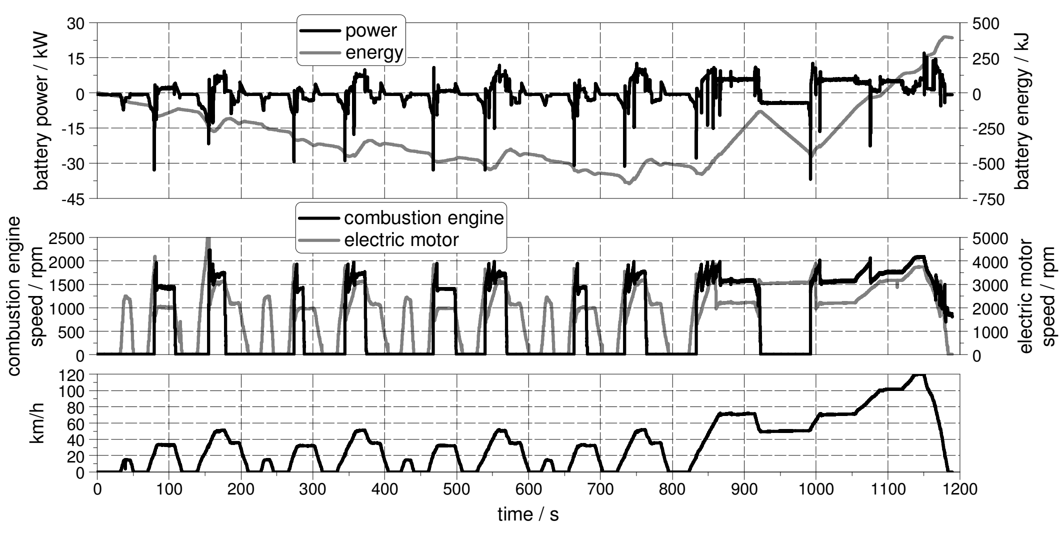


Fig. 5: 7H-AMT demonstrator vehicle in NEDC cy

A very important part of the fuel efficiency improvement is the hybrid strategy that has been developed for 7H-AMT within the research project. It is based on searching the minimum out of cost

Moreover, at the end of the shown cycle the energy level of the battery is significantly higher than at the beginning. This shows that the measured improvement in fuel efficiency is still conservative and robust and gives more space for further improvements.

Input Torque Sensing

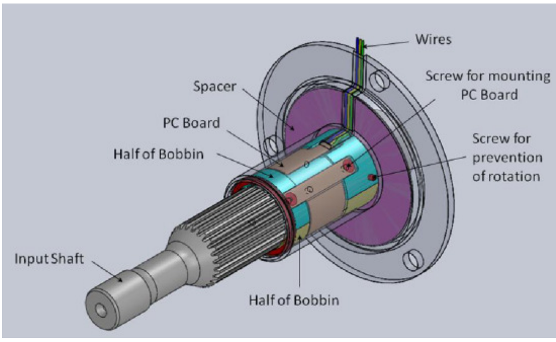


Fig. 6: Torque sensor integration

Methode Electronics, Inc. has developed a mass production-ready torque sensing technology called „MagnetoElastic“. This technology can be applied to transmission shafts and does provide non-contact, highly precise torque readings in real time [4]. In cooperation with Methode Electronics, Inc. it was possible apply this technology to the combustion engine input shaft of 7H-AMT by integrating the sensor into the existing clutch release mechanism.

The development of functionalities including this torque sensor signals has just started and further investigations will show the potential of such a device. In future applications the torque signal will be used for several different functions, e.g.:

- Adaption of clutch kiss-point
- Adaption of relationship between clutch torque and position of the clutch actuator
- Adaption of safe open point
- Torque control during slip-start of combustion engine out of pure electric driving
- Torque control during shifts with electric torque support

The advantage of a torque signal coming directly from a sensor is the reliability of a measurement in contrast of using model based torque signals from engine and clutch. Therefore improved quality, performance and robustness of shift events is expected in future investigations. The following descriptions clarify part of the objectives achieved at the software.

Adaption of clutch kiss-point

The kiss-point adaption function uses the torque signal to recognize exactly where the clutch is located when it starts transferring torque. When the kiss-point is requested, the function moves the clutch nearby a previously stored kiss-point and continues closing it slowly until it starts transferring torque again and stores the new kiss-point value found.

Adaption of clutch torque vs. position

The torque vs. position adaption is based on the torque capacity from the torque sensor and the position from the position sensor when the clutch is slipping. The measurements are used to slightly modify the characteristic torque-position curve. The adapted curve is then used as a pre-control for the position regulation by interpolating the target position out of the target torque

Torque control during slip-start of combustion engine

During a slip-start of the combustion engine out of electric driving, the torque signal from the sensor is used to determine how much additional torque must be delivered by the electric motor to start the combustion engine while keeping the output torque constant. The usage of the sensor replaces the torque model of the engine, which is normally very poor at low speed, and enables a softer start of the combustion engine.

References

[1] Hellenbroich, Gereon; Rosenburg, Volker
“FEV’s new parallel hybrid transmission with single dry clutch and electric torque support” VDI-Berichte 2071

[2] Kirschstein, Stefan; Remelhe, Filipe; Stolze, Bernd
“Efficient Transmission Application by Using Modern Offline Tools”; Proceedings of 8th CTI International Symposium of Innovative Automotive Transmission, Berlin; 2009

[3] Stapelbroek, Michael; Gasper, Rainer; Duindam, Coen; Pischinger, Stefan; Abel, Dirk
“Europa Hybrid: Validierung der Regelungsalgorithmen für einen innovativen Hybridantriebsstrang”
Simulation und Test für die Automobilelektronik
Berlin; 2010

[4] Fuji, Yuji; Greene, Tom
“MDI Magneto-Elastic Torque Sensor for Automatic Transmissions”
4th CTI-Symposium Automotive Transmissions North America 2010