

# **Shifting Optimization of Face Dog Clutches in Heavy Duty Automated Mechanical Transmissions**

Theses

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# 1 Introduction and research goal

Automated Mechanical Transmissions (AMT) with a single dry clutch and a constant mesh gearbox are gaining more and more popularity in the category of heavy duty commercial vehicles. As the manual ones, heavy duty AMTs are generally designed with three stages having split and range gears before, respectively after the main gearbox, all integrated in a common housing, this way quadrupling the gears of the main gearbox including the reverse gear as well. The clutch and the gearshifts rods are not actuated manually by the driver, but through actuators controlled electronically by a joint Transmission Control Unit (TCU). As the compressed air system is implemented in heavy duty vehicles for the brake system anyway, the transmission is usually also actuated electro-pneumatically. Processing the signals of the transmission-related sensors (e.g. clutch position, gearshift rod positions, gearbox shaft speeds, road climb angle, etc) and those available on the vehicle's CAN communication system, the TCU is capable of recognizing the vehicle's operating condition. It is also enabled to override the Electronic Engine Control (EEC) for short periods; consequently, the TCU software determines and shifts the optimal gear without any driver interaction.

The at least partial equalization of the mismatch speed of the dog clutches in the main gearbox required for the engagement is possible through the coupled engine, clutch and gearbox control without providing every single dog clutch with a synchromesh mechanism. During gear shifts, the TCU overrides the EEC to control the engine speed to the level required in the gear to be shifted, which speed corresponds to the perfectly synchronized speed of the input shaft, anyway. The input shaft speed can quickly be matched to the controlled engine speed through partial or full clutch engagement to synchronize the main gearbox. Consequently, AMT gearboxes – unlike manual ones – have a main gearbox with centrally synchronized dog clutches instead of individual synchronization. The omission of the separate synchromesh mechanisms reduces the mechanical complexity and installation space therefore enables the widening of gearwheel width within the same gearbox housing this way increasing the specific weight of the gearbox. However, even engines with advanced engine brake systems have slower dynamics for speed reduction as for speed increase. Therefore at upshifts and at gear shifts from neutral gear – when the input shaft has to be slowed down to reach the synchronized speed – the speed reduction is usually aided or accomplished alone by an additional gearbox actuator, the so-called countershaft brake controlled by the TCU.

Dog clutches are simple locking coupling devices made up of two engaging elements used to lock a gear wheel to its shaft by means of meshing teeth in a shape locking manner. The first engaging element called as sliding dog or sleeve is locked to the shaft in a torque secure manner, but can be displaced axially through the corresponding shift fork. The second engaging element is generally integrated in the gear wheel. The locking or the engagement is realized through the meshing teeth when the sliding dog is in the engaged axial position. Regarding the geometry of the tooth faces, dog clutches can be divided into two basic types: standard and face dog clutches. Face dog clutches – investigated in this Thesis – have teeth with flat face areas, the face areas of the sliding dog and the gear wheel are thus possible to slide on each other before the engagement (Figure 1).

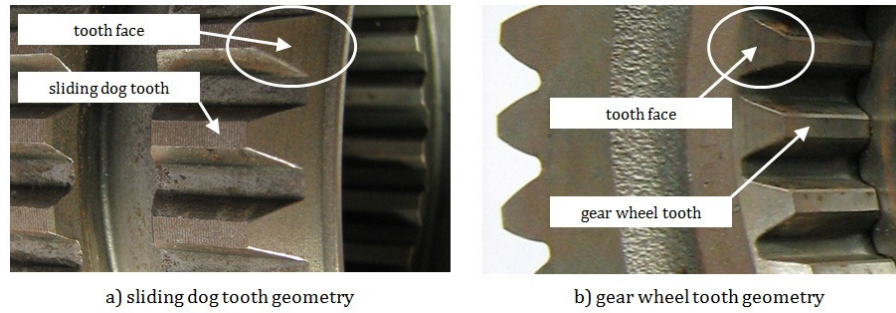


Figure 1. Face dog clutch of the investigated gearbox

The transmission control software according to the state-of-the-art utilizes complex algorithms to reduce to speed difference i.e. the mismatch speed between the meshing elements of the dog clutch in order to ensure the engagement in a pre-defined zone of mismatch speed, ensuring the comfort and lifetime requirements and considered as the synchronized state of the dog clutch. The optimal mismatch speed zone is on one hand limited by keeping the torsional vibrations after the engagement as low as possible, on the other hand by avoiding the permanent tooth-on-tooth situations which are developed when the face friction torque between the sliding face areas reduces the mismatch speed to zero before the engagement, and thus the sliding dog is trapped at incomplete stroke and the engaging elements rotate together in a state which is inappropriate for torque transfer.

The quality of the shifting of the centrally synchronized dog clutches has a determining factor in the harshness of the whole gearshift process, and therefore needs a continuous improvement to meet the ever increasing expectations of the costumers. However, considering a mismatch speed interval as the synchronized state of the dog clutch is a legacy from other automotive applications of dog clutches, and does not consider the principally different operating conditions in a heavy duty gearbox caused by the actuation of the countershaft brake before the engagement. A pre-defined targeted mismatch speed interval is in some cases too high and causes besides the increased shifting noise an unnecessarily high mechanical load and wear of the dog clutch, or it is too low in some other cases, and the engagement ends up unsuccessfully in permanent tooth-on-tooth situation already mentioned above.

The aim of this Thesis is to deeply investigate the engaging capability of face dog clutches with special respect to the interactions with the countershaft brake, and this way develop a more sophisticated definition for the optimal engaging conditions or synchronized state for gear shifts with countershaft brake actuation. The enhanced definition of the synchronized state shall reduce the necessary mismatch speed at the engagement, this way reducing the mechanical load of the components and consequently, the gearshift noise, and at the same time, prevent the unwanted tooth-on-tooth situations.

## 2 Research steps and achievements

In compliance with the target setup, the mechanical model of the dog clutch covering the time range until the end of the face friction phase was first formulated in order to investigate the development of permanent tooth-on-tooth situations. The variation of the outcome of the engagement from one gearshift to another at some mismatch speeds is caused by the variation of the initial relative angular position of the meshing elements. The non-deterministic outcome of the engagement is considered by handling the initial position as a random variable of uniform distribution. The

engaging capability was characterized with the engaging probability curve giving the probability of the successful engagement as a function of the mismatch speed. The effect of the reduced input and output side inertias were highlighted, this way explaining the different engaging capability of the same meshing geometry when engaging different gears or the differences between test bench and vehicle application.

The model results were validated with test bench measurements. The gearbox test bench used in this Thesis includes a heavy duty AMT gearbox with electric motors driving the input, respectively output shafts. The clutch is also part of the hardware loop, though not mounted on the gearbox shaft. The speed of the electric motors is controlled according to the signals produced by a longitudinal real-time full vehicle model, the gearbox and the clutch is operated with full functionality by a transmission control software developed especially for testing purposes. The engaging probability of the face dog clutches of the tested gearbox was emitted with a series of measurement results, including more than 5000 gear shifts and evaluated statistically using the law of large numbers. A good correlation was found between the calculated and measured values.

As the second step, the mechanical model of the dog clutch was completed with the detailed mechanical – pneumatical model of the countershaft brake in order to reveal the effect of preceding countershaft brake actuation on the dog clutch engagement. Furthermore, the friction losses of the gearbox input side are also considered. The extended model includes a set of algebraic and ordinary differential equations and was implemented in MATLAB/Simulink simulation environment. The unknown parameters were identified and the model validated with measurement data. The engagement probability curve was generalized by picking up the countershaft brake chamber as the second variable for the engagement probability map. A region was found on the mismatch speed – countershaft brake chamber pressure plot with engagement probability values lower than 1, and referred as the uncertain zone. The variation of the shape of the uncertain zone was investigated in details, and according to the way of variations, three vehicle conditions – not moving, slowly moving and moving – were separated from each other.

Based on the simulation results regarding the engaging capability of face dog clutches at gear shifts with countershaft brake actuation, the state-of-the art definition of the synchronized state was enhanced. The optimal engagement conditions were defined as the region on the mismatch speed – countershaft brake chamber plot with the smallest possible mismatch speeds but still outside the uncertain region. The post-engagement torsional vibrations are this way reduced compared to the state-of-the art without the possibility of permanent tooth-on-tooth situations. Finally, in order to prove the feasibility of the new, enhanced definition of the synchronized state of the face dog clutch, a synchronizing algorithm is developed and implemented in the transmission control logic of a heavy duty automated gearbox. The algorithm was based on curves generated with numerical simulations and stored in the control logic this way making the algorithm flexible and easily adoptable to different types of gearboxes. The algorithm was capable of controlling the countershaft brake in a way that the engagements take place inside the enhanced synchronized state, this way proving the feasibility of the new definition of the synchronized state, which was verified through test bench and vehicle measurements.

### **3 Practical benefits, further work**

The practical application of the new results regarding the optimization of the engagement process of face dog clutches, i.e. the enhanced definition of the synchronized state and the synchronizing

algorithm based on the new definition, results in a direct improvement of the gearshift comfort and component lifetime. As a further step, a similar, enhanced definition of the synchronized state is possible to be worked out for the other basic type of dog clutches. For standard tooth dog clutches, the engagement may be considered as unsuccessful either when a permanent tooth-on-tooth situation or a re-bounce occurs, the latter however does not require a new engagement attempt but comes with an intensive crack-like noise and wear of the meshing geometry.

## 4 Theses

The new scientific results of this Thesis can be summarized according to the following theses. The labels of the related publications (as given in Section 5) are indicated in parenthesis.

**Thesis 1** The coupled mechanical – pneumatical model of a face dog clutch – countershaft brake system has been developed with a special modelling purpose to describe the engaging capability of the face dog clutches in heavy duty Automated Mechanical Transmissions ([P2], [P4], [P5]).

1. The model is defined by a set of algebraic respectively ordinary differential equations, and considers all driveline elements reduced to the gear wheel respectively sliding dog.
2. The single input of the model is the duty of the countershaft brake control solenoid valve. The outputs of the model are the countershaft brake chamber pressure, the rotational speed of the gear wheel and the sliding dog and specially, an unusual model output is the probability of the successful dog clutch engagement without a permanent tooth-on-tooth situation.
3. The unknown parameters of the model have been identified with the least squares fit principle using the continuous time model and discrete time series of test bench measurement results.
4. The identified model has been validated with independent measurements, in particular, the model results regarding the engagement probability were validated through the statistical evaluation of a large set of measurement results using the law of large numbers.
5. In order to achieve some non-standard modelling goals, the mechanical model was transformed into a reverse time model to simulate the synchronization process *reverse* in time.

**Thesis 2** Using the probability of the successful engagement as the measure of the engaging capability of the face dog clutch, the engagement probability map was introduced to characterize the engaging capability at gear shifts with countershaft brake actuation ([P4]).

1. The engagement probability map gives the probability of the successful engagement without the occurrence of permanent tooth-on-tooth situations as a function of the mismatch speed and the countershaft brake chamber pressure at the engagement.
2. Under specific vehicle moving conditions, a region with probability values lower than 1 was identified in the engagement probability map, and referred as the uncertain zone, not ensuring the successful face dog clutch engagement.
3. It was shown that the shape of the uncertain zone depends on the shifted gear and changes with the input shaft speed after the engagement considered as a

parameter for the engagement probability map. Three types of vehicle moving states were separated regarding the shape and the character of the variation of the uncertain zone: not moving, slowly moving respectively moving vehicle.

### Thesis 3

Based on Thesis 2, a new, enhanced definition was set up for the synchronized state of the dog clutch, which improves the comfort of gear shifts with countershaft brake actuation compared to the current state of the art, without any compromise regarding the permanent tooth-on-tooth situations ([P3], [P4]).

1. The synchronized state or the zone of optimal engagement conditions is defined as a domain of complex shape on the mismatch speed – countershaft brake chamber pressure plot and depends on the uncertain zone, therefore also on the actual vehicle moving state.
2. For not moving vehicle, the synchronized state is specified by the following definition:

$$S = \{(\Delta\omega_1, p_{csb}) \mid P(\Delta\omega_1, p_{csb}) = 1 \wedge T_{tor,max}(\Delta\omega_1) \leq T_{lim}\}$$

In order to eliminate the backlash side change of the engaging elements and thus to further reduce the gearshift noise, the synchronized state for moving vehicle is restricted to negative mismatch speeds:

$$S = \{(\Delta w_1, p_{csb}) \mid P(\Delta w_1, p_{csb}) = 1 \wedge T_{tor,max}(\Delta w_1) \leq T_{lim} \wedge \Delta w_1 < 0\}$$

3. Compared to the current state of the art, the enhanced synchronized state enables the reduction of the maximum of the peak value of the post-engagement torsional vibrations and ensures the success of the engagement for the first attempt by completely preventing the development of permanent tooth-on-tooth situations.

### Thesis 4

The feasibility of the practical application of the synchronized state according to Thesis 3 was proven through a look-up based synchronization algorithm developed for an existing automated mechanical gearbox ([P3]).

1. The implementation of the enhanced synchronized state into the transmission control system of an existing heavy duty Automated Mechanical Transmission was achieved without any hardware adaptation or increasing the actuation number of the countershaft brake control solenoid valve.
2. The developed synchronization algorithm utilizes two different sub-algorithms depending on the vehicle's moving state. The sub-algorithms for not moving respectively moving vehicle together cover all possible cases of gear shifts with countershaft brake actuation, and both operate with pre-defined look-up curves generated by numerical simulations and stored in the algorithm.
3. The vehicle is considered as moving if the vehicle speed is at least the speed corresponding to the half of the engine low idle speed in the gear to be shifted, and considered as not moving below that speed.
4. The function of the synchronization algorithm was evaluated with results of test bench and vehicle measurements.

## 5 Publications

### 5.1 Publications directly related to the theses

The results of the Ph.D. thesis have been presented at conferences or published in journals as follows. The publication [P3] presented at the FISITA 2010 World Automotive Congress was awarded by the Federation Internationale des Sociétés d'Ingénieurs des Techniques de l'Automobile (FISITA) with the „Outstanding Paper Award”.

- [P1] Bóka, G., Márialigeti, J., Lovas, L. and Trencsényi, B. External synchronization strategies for automated mechanical transmissions with face dog clutch and countershaft brake. *Buletin Stiintific-Universitatea Din Baia Mare-Seria C Fascicula Organe De Masini Tribologie Constructii De Masini XXIII: pp. 75-80. (2009)*
- [P2] Bóka, G., Márialigeti, J., Lovas, L. and Trencsényi, B. Automatizált nehéz haszonjármű sebességváltó elektro-pneumatikus előtétengelyfékének modellezése. *GÉP LX:(10-11) pp. 18-21. (2009)* In Hungarian
- [P3] Bóka, G., Trencsényi, B. and Németh, H. Look-up Based Synchronizer Logic for the Effective Actuation of the Countershaft Brake in a Heavy duty AMT with Face Dog Clutch. In: *Proceedings of FISITA World Automotive Congress 2010. Budapest, Hungary, GTE, pp. 1-6. Paper F2010C097 (2010), granted with ‘Outstanding Paper Award’*
- [P4] Bóka, G., Lovas, L., Márialigeti, J. and Trencsényi, B. Engagement capability of face-dog clutches on heavy duty automated mechanical transmissions with countershaft brake. *Proc. IMechE, Part D: J. Automobile Engineering, 224 (D9), pp. 1125-1139. DOI 10.1243/09544070JAUTO1435 (2010)*
- [P5] Bóka, G., Márialigeti, J., Lovas, L. and Trencsényi, B. Face dog clutch engagement at low mismatch speed. *Periodica Polytechnica Ser. Trans. Eng. 38/1 pp. 29-35. (2010)*

### 5.2 Publications indirectly related to the theses

The following publications do not include any of the theses presented in this work; however, they are strictly related to the topic and referenced in the main body of the Thesis:

- [P6] Bóka, G. and Lovas, L. Szinkronizáló rugós központosító mechanizmusainak hatása a kapcsolóhüvely axiális dinamikájára. *GÉP LIX:(10-11) pp. 7-10. (2008)* In Hungarian
- [P7] Bóka, G., Trencsényi, B., Németh, H. and Palkovics, L. Elektromechanikus működtetőegység fejlesztése automatizált nehézhaszonjármű-sebességváltóhoz. *A Jövő Járműve 2010: (1-2) pp. 64-69. (2010)* In Hungarian
- [P8] Bóka, G., Trencsényi, B., Németh, H. and Palkovics, L. Hajtáslánc irányító funkciószoftver fejlesztése automatizált nehéz haszonjármű sebességváltóhoz. *A Jövő Járműve 2010: (3-4) pp. 46-52. (2010)* In Hungarian