ČESKÉ VYSOKÉ
UČENÍ TECHNICKÉ
V PRAZE

FAKULTA
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TEZE
DISERTAČNÍ
PRÁCE

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
FAKULTA STROJNÍ
ÚSTAV AUTOMOBILŮ, SPALOVACÍCH MOTORŮ A KOLEJOVÝCH VOZIDEL

TEZE DISERTAČNÍ PRÁCE

DOG CLUTCH WITHOUT ANGULAR BACKLASH

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Studijní obor: Dopravní stroje a zařízení

Školitelka: doc. Dr. Ing. Gabriela Achtenová

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S disertací je možno se seznámit na oddělení vědy a výzkumu Fakulty strojní ČVUT v Praze, Technická 4, Praha 6.

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1. CURRENT STATE OF KNOWLEDGE

For shifting gears mechanically in passenger car gearboxes, two design options are most widely used – a synchronizer or dog clutch; [1].

Fundamentally, the synchronizer incorporates two clutch principles in one unit. There are friction surfaces that are responsible for matching the angular speed (analogy with general friction clutch design) and toothing responsible for torque transfer in the engaged state (analogy with general dog clutch design). This ensures smooth gearshift with no need for external synchronization. Synchronizers are therefore widely used in gearboxes shifting with power interruption (manual and automated gearboxes) and dual clutch gearboxes; [2].

The simplest face dog clutch design (see Figure 1) consists of a clutch body (1) fixed to the gearbox shaft. Then there is a sliding dog (2) – the main engaging element. It cannot rotate freely but can be displaced axially through the corresponding shift fork. The second engaging element is generally integrated into the shifted gear wheel (3). The locking or engagement is realized through the mesh of the dogs when the sliding dog is in the engaged axial position.

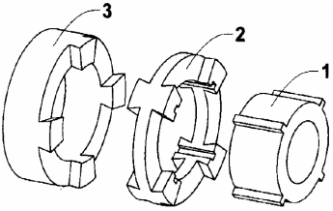

Figure 1: Face dog clutch components; [3]

The dog clutch is a suitable candidate to replace the synchronizer, especially in the case of using external synchronization. In the default configuration, dog clutches cannot offer the same qualities as the synchronizer, but the dimension and weight savings are significant; [4]. Gearboxes must be equipped with the same number of synchronizers as they have synchronized gears, even though adjacent gears usually have their pair of clutches merged into one, which operates them both. Another advantage of the dog clutch is the ability to shorten the gearshift duration when using sufficiently powerful external synchronization system, especially for lower gears (i.e., gears with high ratio); [5]

Dog clutches without synchronization are not widely used in passenger car gearboxes. One of the reasons is the angular backlash in the engaged state which is caused by the commonly used shape of the dogs with negative angle of the sides – see Figure 2 a); [6] The backlash is necessary for successful

engagement. Using positive angle of the sides as in Figure 2 c) would be favorable for minimizing the angular backlash. However, the axial force arising on the sides of the dogs when transmitting torque in this case points out of the mesh which leads to unwanted disengagement.

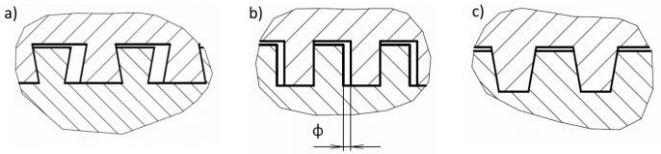

Figure 2: Types of face dog dogs regarding to the side angle of the dogs

Text of the thesis lists various dog clutch designs focused on minimizing the angular backlash – ranging from 1930 patent [7] to modern solutions for racing [8] and dedicated hybrid transmissions [9]. Their components, principle, advantages and disadvantages are described.

Furthermore, Czech Technical University in Prague has been active for several years in the field of design and testing of shift mechanisms, as well as in the design of new gearshift clutches; [10]. Five designs are presented including the proposal of a *dog clutch with blocking mechanism* – result of the author's diploma thesis (see Figure 3). The idea is to complement a standard dog clutch with positive angle of the dogs by a blocking mechanism. The shape of the dogs minimizes angular backlash in engaged state, and the mechanical blocking mechanism prevents unwanted disengagement under load. Disengagement is possible under all conditions, even under load. Gearshift force is significantly lower than the axial force acting on the blocking mechanism under torque transmission.

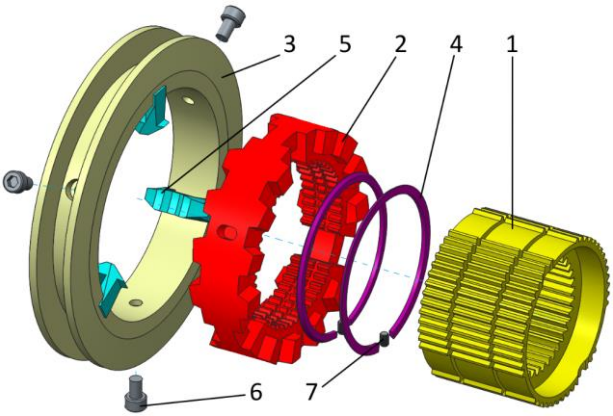

Figure 3: Dog clutch with blocking mechanism – exploded view [11]
1 – hub; 2 – sliding dog; 3 – gearshift sleeve; 4 – blocking rings; 5 – gearshift stones; 6 – gearshift pins; 7 – detent pins

Electric and hybrid vehicles with electric motor suitable for external synchronization provide biggest potential for the usage of dog clutches for shifting gears. The thesis describes dedicated hybrid transmissions using dog clutches, such as from Renault [12], Aisin [9] or AVL [13].

A dog clutch is also used in the 2-speed transmission for electric vehicles – Porsche Taycan and AUDI e-tron GT at their rear axles; [14]. Here the dog clutch is responsible for shifting first gear and parking lock. It connects the sun of the planetary gear set to the stator and only blocks rotation in one direction, the other direction is blocked by freewheel (see Figure 4).

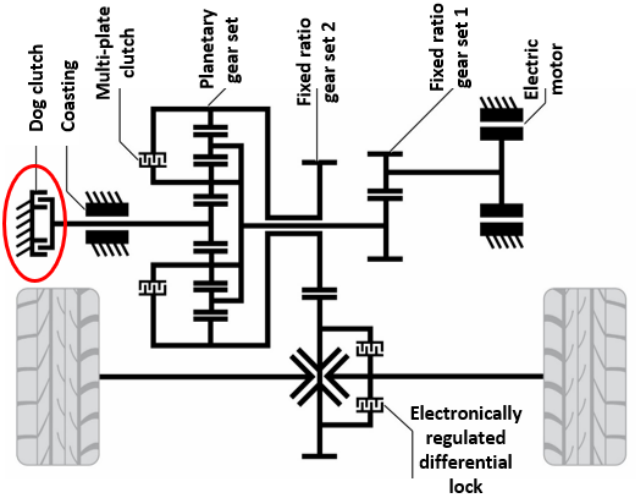

Figure 4: AUDI/Porsche 2-speed EV transmission equipped with a dog clutch [14]

The known issue of this solution is that after engaging the dog clutch under particular conditions, disengaging may not be possible. This happens due to elasticity of the components and pre-tensioning the dog clutch. Therefore, electronics and sensors are necessary to monitor the conditions and prevent risky engagement. As a result, the total amount of recuperation is limited as that is not possible without the dog clutch engaged. A dog clutch with positive angles on the dogs' sides capable of disengaging anytime would not have to deal with such a problem.

2. OBJECTIVES

Based on the research of existing gearshift mechanisms and their properties, the following objectives of the thesis were defined:

1) Design a gearshift mechanism based on the dog clutch capable of fulfilling the following requirements:
   - Angular backlash in the engaged state is minimized.
   - Disengaging is possible even under load.

   The positive angle of the sides of the dogs may be necessary to comply with these requirements. Furthermore, the dog clutch must be competitive with other mass-produced dog clutches and must therefore meet the other standard dog clutch properties.
2) Verify the gearshift mechanism experimentally using a physical prototype and a suitable test bench. Testing will focus on the gearshifts and torque transmission and can be divided into the following areas:
   - Functionality.
   - Service life.
   - NVH and comfort.

3. SOLUTION

Based on the research, the author decided to continue in the development of the *dog clutch with blocking mechanism*. Uniqueness of the design was later confirmed by patent No. 307443 *'Řadicí spojka'* [I.] by the Czech Office of Industrial Property and utility model *'Schaltungskupplung'* [II.] by the German Patent and Trade Mark Office.

This decision was also supported by early tests of the first clutch prototype manufactured according to the drawings included in the author's diploma thesis. The initial design and test results were presented in papers [III.], [IV.] and article [IX.]. However, an improvement potential was identified for both the dog clutch and the test bench.

The final design of the dog clutch with blocking mechanism is a result of multiple iterations. Key features described in the patent and utility model were carefully retained in the design and therefore the patent protection still applies. The final design was presented in [V.] and later [VIII.].

It consists of hub (1) fixed to the gearbox shaft, sliding gear (2) which can move axially to engage selected gear, gearshift sleeve (3) to control the sliding gear movement and blocking ring (4) to secure the sliding gear in desired positions (see Figure 5). Sliding gear is divided into two halves connected by screws (5) and pins (6) because of assembly reasons. One

blocking ring is enough to secure sliding dog in all three positions (engaged/neutral/engaged) and gearshift sleeve in neutral position as well. No modifications of the standard MT/AMT gear selector mechanism are needed.

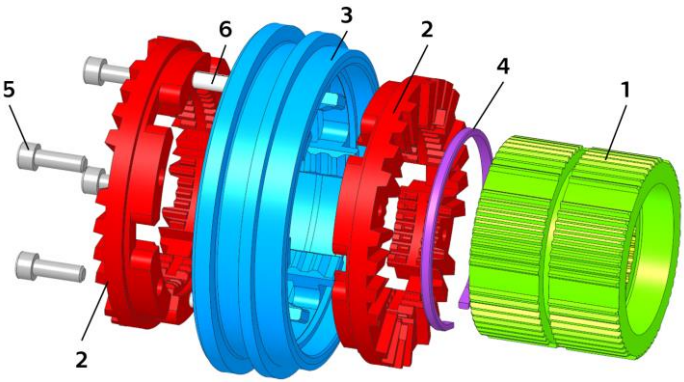

Figure 5: Final dog clutch with blocking mechanism design

In the engaged state, the whole axial force acting on the dogs of the sliding gear is secured by the blocking ring. For the gearshift process, an axial gap of defined size between the sliding gear and gearshift sleeve is crucial. When the engagement or disengagement starts, the gearshift fork always slides the gearshift sleeve first. The gearshift sleeve compresses the blocking ring. As the process continues, the gap between the sleeve and sliding dog is reduced to zero and the sleeve pushes the sliding gear in the desired direction – it is no longer blocked by the ring.

The dog clutch with blocking mechanism was initially designed for cooperation only with shifting mechanism based on the standard MT or AMT system. To make it as widely usable as possible, modifications were proposed to make it compatible with sequential shifting. The idea of adapting the dog clutch for sequential shifting is based on adding a wave spring between the sliding dog and the selector fork (see Figure 6).

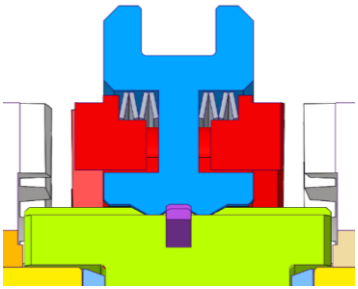

Figure 6: Dog clutch with additional disc springs – cut section

As a result, the travel of the selector fork would always be longer than the travel of the sliding dog. The difference between them would be compensated by deformation of the disc spring to provide secure blocking under every circumstance. Multi-body simulation model was created in cooperation with University of West Bohemia to verify this adaptation and results were presented in paper [X.]. More details about the simulation model were presented in [VI.] and [VIII.].

4. VERIFICATION

Fulfillment of the requirements put on the dog clutch with blocking mechanism had to be verified with respect to the dog clutch design and thesis objectives. Prototypes were made (Figure 7) for testing in the Škoda MQ200 five speed mechanical gearbox.

Figure 7: Prototypes of the clutch for the 1st, 2nd, 3rd and 4th gear

The testing was mostly performed at the test bench initially designed for testing of standard gearshift mechanisms. Therefore, many modifications and upgrades were necessary prior to the testing. Most importantly, external synchronization using an electric motor was added to the input shaft together with a controllable friction clutch system for further research of the behavior during gearshift. A completely new control system in LabVIEW was created.

The updated layout of the test bench can be seen in Figure 8. Addition of external synchronization and friction clutch were presented in [VII.] and [XI.].

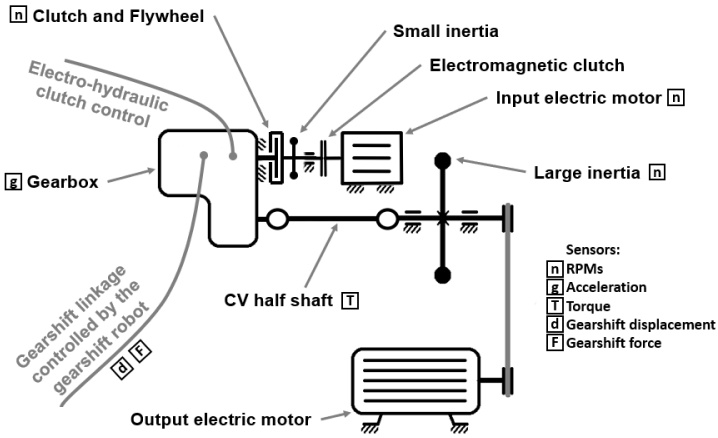

Figure 8: Updated test bench with major measurement locations

Functionality was tested in the first place. Before assembly into the gearbox, the scales were used to measure the gearshift force necessary for compressing the blocking ring. Afterwards, the prototypes were assembled into the gearbox and the gearshifts were monitored and evaluated using a video probe at low angular speeds (see Figure 9). Then the testing continued for standard operation conditions with focus on the clutch behavior, gearshift times etc.

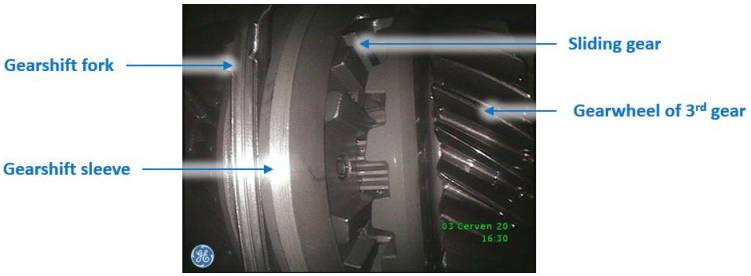

Figure 9: Gearshift verification using video inspection probe

Service life tests were focused on the blocking ring which is considered the most critical component of the clutch subjected to cyclic bending stress. After 720,000 cycles, there was no plastic deformation of the ring, the outer diameter still complied with the dimension required in production drawing. The most visible wear was located at the outer diameter, at the edges where the blocking ring is compressed by the gearshift sleeve, near the ends of the C-shape – see Figure 10 and Figure 11.

Figure 10: Ring after service life test

Figure 11: Ring after service life test – detail

Automotive gearboxes have been thoroughly studied regarding the NVH due to torque transmission and high-speed rotational movement. Many sources and papers addressing gear noise and its minimization can be found. However, very little research is available for NVH of the gearshift mechanisms, especially methodology and measured values for reference. For this reason, methodology based on vibration and noise measurement and comparison of dog clutch with blocking mechanism and synchronizer in identical gearbox at the test bench was designed.

Overall, the results indicate that the NVH and comfort of the dog clutch with blocking mechanism during gearshift should be manageable in real operation, especially for the intended mismatch speed of 100 min^{-1}, where its performance is comparable or slightly worse than the synchronizer. However, as mentioned previously, the measurement did not follow any standardized methodology, and the results should serve only as an approximate comparison.

Nevertheless, it would require a carefully designed shape of the gearshift dogs and precise external synchronization to match the performance of the synchronizer in a wider range of mismatch speed.

5. CONSEQUENCES FOR SCIENCE AND INDUSTRY

This chapter summarizes the outcomes of the thesis from the perspective of their benefits for scientific and industrial environment and their possible utilization.

Gearbox Test Bench with External Synchronization and Clutch Control

The modifications of the inertia test bench greatly expanded the possibilities of testing and research of the gearshift mechanisms, gearboxes, and their behavior during gearshifts under wide range of operational conditions. External synchronization is now independent on the tested gearbox and easily controllable, the effect of the friction clutch on gearshift quality can be tested, the accuracy of the measured data was improved, NVH measurement and

analysis is now possible, and sequences of gearshifts with variable inputs can be automatically tested.

All these improvements resulted in a new research project in cooperation with the industrial partner – ŠKODA AUTO, a.s. The research was focused on improving the gearshift quality of an automated hybrid transmission using innovative gearshift strategies. The experimental part of this research was carried out completely at the inertia test bench.

Gearshift Mechanism without Angular Backlash

The shape of the dogs of the dog clutch with blocking mechanism is absolutely unique in the field of passenger car gearboxes. Positive angle of the sides guarantees minimal angular backlash in the engaged state, approximately one to two orders of magnitude smaller compared to conventional dog clutches. This improves driving comfort due to much lower shocks when torque direction changes.

Even though this design can be found in specific applications (e.g., differential locks), so far it must have generally been accompanied by a strong detent system and correspondingly strong and heavy actuation system. This does not apply to the new dog clutch with blocking mechanism – the gearshift force required for its engagement and disengagement is comparable to other conventional gearshift mechanisms and approximately two orders of magnitude lower than the axial force it can withstand under full load in the engaged state.

Furthermore, the clutch can always be disengaged even under load. The gearshift force is independent of the load and stays constant under all conditions. This property would for example solve the issues and limitations of Porsche and AUDI EV gearbox caused by pre-tensioning of the gearshift clutch. Both companies were approached with an offer including a description of the solution of the problem using the dog clutch without angular backlash.

Gearshift Mechanism for Gearboxes with External Synchronization

The design was thoroughly tested and validated. The dog clutch with blocking mechanism is a reliable solution of gearshifts with external synchronization. Its potential is amplified by the fact that the industrial partner was actively participating in the whole development process.

Tools for Design and Simulation of the Gearshift Mechanism

For those interested in the dog clutch with blocking mechanism, digital tools were prepared to make the consideration and implementation easier. The design program can serve for quick acquisition of approximate packaging dimensions for the intended use supplied by basic strength calculations. A

data set of measured gearshifts is prepared to validate future simulation models for gearshift optimization.

6. CONCLUSION AND FUTURE WORK

The use of externally synchronized dog clutches can contribute to optimizing the efficiency and costs of future electric and hybrid vehicles. Comfortable and fast gearshifts and noiseless torque transmission are crucial for the acceptance of such powertrain concepts.

The new patented dog clutch with blocking mechanism retains all the advantages of a conventional dog clutch and additionally provides the benefits of minimal angular backlash in the engaged state and the ability to disengage anytime, even under load. It is purely mechanical and compatible with standard gear selector mechanisms, including sequential shifting, without additional modifications.

The angular backlash is less than 0.1° and is ensured by the gearshift dogs with a positive angle of the sides. All operating positions of the clutch (engaged, neutral) are secured by one blocking ring only. Due to this unique ring, the clutch can withstand axial forces due to torque transmission, which are several orders of magnitude higher than the force needed for engagement and disengagement. Unwanted disengagement is prevented.

The design of the dog clutch was optimized for effective serial production using powder metallurgy. Comprehensive strength and service life calculations were performed, and a parametric design program was created. The blocking ring and gearshift dogs were detected as the most critical parts of the clutch and their calculations are described in detail in the thesis. The service life of the blocking ring was evaluated using both analytical approach and simulation to ensure that it can last for 700,000 cycles.

The clutch prototypes were manufactured and assembled into a standard mechanical five-speed gearbox. The possible axial saving for this gearbox when using dog clutches without axial backlash instead of the original synchronizers is up to 30 mm. The prototypes successfully passed the functionality and service life testing at the test bench. Furthermore, testing of the gearshift quality and behavior during torque transmission was carried out – the results and comparison with synchronizer are presented in the thesis.

To make testing possible, the gearbox test bench was thoroughly refined and upgraded. The modifications included especially the addition of external synchronization using an electric motor, friction clutch control, and a new control system for the entire test bench. Now it is possible to test and evaluate any gearshift mechanism assembled into a gearbox. The test bench is also suitable for the research of innovative gearshift strategies that utilize friction clutch control.

In the following steps of the research, it would be suitable to assemble a gearbox with the dog clutches with blocking mechanism into a vehicle and perform tests that focus on gearshift quality and comfort perceived by the driver. Especially the noise data would better reflect real operation than those measured at the test bench. This would help to define more precisely the mismatch speed limitations and accuracy requirements of the external synchronization.

Moreover, for further optimization of the gearshift comfort through the design of the dogs, completion of the multi-body simulation program would be beneficial. The model should be expanded to include the entire powertrain representation with a focus on the torsional stiffnesses of the components. This would allow for the finding of a suitable geometry for a specific application.

Furthermore, the design of the dog clutch with blocking mechanism could be optimized for even greater axial space savings than that mentioned above for the manufactured prototypes. These were limited by the boundary conditions given by the requirement of easy assembly into the test gearbox. The reduction in axial length will be reflected mainly in the weight savings of the gearbox, including the shafts, the gearbox housing, or the gear selector mechanism. Shortening the axial length of the gearbox also reduces the bearing distance of the shafts, which favorably reduces shaft deflections and improves the quality of the gear mesh.

The design of the clutch and the text of the thesis focused on application in automotive gearboxes. It would be advisable to conduct a search for possible application in the drivetrains of commercial vehicles or heavy industrial vehicles and machines.

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ANOTACE V ČESKÉM JAZYCE

Zubová spojka bez úhlové vůle

Zubové spojky jsou jednoduché a levné mechanismy pro řazení převodových stupňů. Jejich použití v automobilových převodovkách však bylo omezeno úhlovou vůlí v zařazeném stavu a z toho plynoucím zhoršením jízdního komfortu.

Na základě rešerše stávajících řešení byla vyvinuta a později patentována nová a unikátní konstrukce zubové spojky bez úhlové vůle. Vůle je minimalizována díky čistě mechanickému jisticímu mechanismu. Nová zubová spojka je zaměnitelná za konvenční mechanismy řazení bez dodatečných úprav a vyžaduje systém vnější synchronizace otáček.

Konstrukce nové zubové spojky s jisticím mechanismem je detailně popsána se zaměřením na inovativní části – řadicí ozubení a jisticí mechanismus. Byla provedena adaptace na sekvenční řazení a spojka byla doplněna návrhovým a simulačním programem.

Dva prototypy spojky byly vyrobeny ve spolupráci s průmyslovým partnerem a testovány na zkušebním stanovišti uvnitř převodovky. Zkoušky prototypů byly zaměřeny na funkčnost, životnost a komfort při řazení. Zkušební stanoviště muselo být výrazně upraveno a zmodernizováno, aby byly tyto zkoušky možné.

Zkoušky byly vyhodnoceny jako úspěšné. Zubová spojka s jisticím mechanismem je vhodná pro řazení převodových stupňů v automobilových převodovkách, zejména hybridních a elektrických vozidel vybavených elektromotorem. Dokáže eliminovat některé nedostatky klasických zubových spojek, jak je popsáno v rešeršní části.