APPLICABILITY OF THE NEW KYOWA HIGH PERFORMANCE SYNCHRONIZER

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ABSTRACT - Synchronized gear shift units are present today in Manual Transmissions (MT) [1], Automated Manual Transmissions (AMT) [2] and Double Clutch Transmissions (DCT) [3], as well as in special applications of commercial vehicle transmissions and 4WD - applications. In any of these applications, but especially in the MT, the acting force and time needed to complete the synchronization are crucial parameters for shift comfort. Although shift comfort is a result of several effects, like double bumps, nibble, driveline vibrations, unlock problems etc., this paper focuses on the shift effort during synchronization as main influence.

This paper introduces a new synchronization concept, the Kyowa High Performance (Hi-Per) Synchronizer “K.H.S.”. Its basic innovation is a small change to the geometry of a standard synchronizer unit, leading to a substantial amplification of the shift force acting at the synchronizer ring. As a result, the required synchronization force is minimized and the shift comfort is substantially improved at the same time. On the other hand, if the synchronization force is maintained, the shift time can be minimized. This paper provides information about the basic design along with sophisticated calculations, simulation and test bench results at all important working conditions. The research also concentrates on suitable friction materials under realistic conditions.

The K.H.S. is therefore able to provide improved comfort and minimized shift effort at virtually no additional costs of production.

INTRODUCTION

Borg Warner (hereafter, "BW") Synchronizers [1] have been applied as standard in Manual Transmissions (MT) for a long period, and conventionally, the multi cone version of a BW synchronizer has been often applied as solution for improving synchronization performance. However, the BW multi cone version may have some problems under certain conditions as listed below.

1) Additional space in radial and axial direction may be required compared to a single cone version.
2) The production cost increase may be larger than the expected additional benefit in synchronization performance.
3) The BW Synchronizer may have its realistic design limit in triple cone design, 4-cone synchronizers have not been applied due to the low potential compared to the high price, tolerance and temperature situation.

Therefore, we are aiming to improve the performance by a new structure synchronizer (see also [4, 5]), which is called Kyowa High Performance (Hi-Per) Synchronizer “K.H.S.”. The “K.H.S.” is verified by hardware prototyping and simulation models, which delivered highly
promising results. Presently we are focusing on the actual applicability for vehicle transmissions.

**BASIC STRUCTURE OF THE NEW KYOWA HIGH PERFORMANCE SYNCHRONIZER**

In many applications of MT, the synchronizer capacity (or friction torque corresponding to the same shifting force) is the limiting factor for shift comfort especially for downshifts in low gears. This leads to one of the main benefits of the K.H.S.

A very effective way to increase the synchronizer capacity is to use the available torque to amplify the axial force on the synchronizer ring. This kind of mechanism has already been successfully applied in drum brake systems with self-servo effect. There have been attempts [6] to put this mechanism into synchronizers as well. A main issue for practical application is to cope with the drag torque that generates a force on the synchronizer ring in neutral position. This can lead to a not intended synchronization process. In other words, although the self-servo effect for increasing the shifting force is remarkably high, there is no reliable and straight forward counter-measure against drag torque generated synchronization.

The new K.H.S. system solves the problem of synchronizing without intention with new H-shaped thrust pieces which prevent forces to act on the synchronizer ring in neutral position. Slopes on the hub and on the thrust pieces generate an additional servo force during synchronization. The basic principle is shown in fig. 1. A section through an example K.H.S. design is shown in fig. 2.

![Fig. 1: Principle of the new Kyowa High Performance Synchronizer](image)
Basically, when synchronizing, a part of the friction torque is used to generate an additional force on the synchronizer ring. The amplification factor (performance ratio, PR) can be easily estimated by the following equation:

\[
PR = \frac{F_m + F_s}{F_m} = \frac{R_{\text{BloTeeth}} \mu \cdot j \cdot R_C}{\tan(\alpha) \sin \theta} \frac{\mu \cdot j \cdot R_C}{\sin \theta} \frac{R_{\text{Servo}}}{\tan(\gamma)} + 1
\]  

(1).

The symbols used in equation (1) are listed in table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Item</th>
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<tbody>
<tr>
<td>(F_s)</td>
<td>Axial servo force</td>
</tr>
<tr>
<td>(F_m)</td>
<td>Manual operating force</td>
</tr>
<tr>
<td>(R_{\text{BloTeeth}})</td>
<td>Blocking teeth radius</td>
</tr>
<tr>
<td>(R_C)</td>
<td>Cone radius</td>
</tr>
<tr>
<td>(R_{\text{Servo}})</td>
<td>Radius of servo slope</td>
</tr>
<tr>
<td>(j)</td>
<td>Number of friction cones</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Blocking teeth angle</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Cone angle</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Servo slope angle</td>
</tr>
<tr>
<td>(\mu)</td>
<td>Friction coefficient of cone</td>
</tr>
<tr>
<td>(PR)</td>
<td>Performance ratio</td>
</tr>
</tbody>
</table>

This equation neglects detent forces, internal friction and other minor influences as well as dynamic effects during shifting.

Basically the performance of a standard Borg Warner Synchronizer depends on the friction diameter, friction coefficient, number of cones, cone angle, etc. The performance of a K.H.S.
compared to a Borg Warner Synchronizer is shown in fig. 3. The amplification factor increases progressively with the performance of the synchronizer friction cones.

In theory, one can achieve any amplification factor simply by changing the servo slope angle. However, the limit is the maximum servo slope angle due to the self lock phenomena. An increased blocking teeth angle also yields higher amplification, but this can cause unlock problems especially at low temperatures depending on the gearbox drag torque.

An example design of a K.H.S. is shown in fig. 4. The three thrust pieces move in axial direction from neutral position to synchronizing position together with the sleeve, which is basically unchanged to the Borg Warner design. Contact between the slopes of the thrust pieces and the hub is avoided in neutral position as explained above. The pre-synchronization force [1] is achieved by springs. This force pushes the synchronizer ring into the right position for the synchronizing process. During synchronization the slopes of the thrust pieces and the hub are in contact generating a servo force acting on the synchronizer ring. The unlocking via the blocking teeth of the synchronizer ring and the sleeve as well as the engaging process is basically unchanged to Borg Warner Synchronizers.
There are not many differences of a K.H.S. design compared to a Borg Warner Synchronizer but some special differences have to be considered during the design process.
The most important difference of the design is the change of overlap length on the chamfer surface while synchronizing with proceeding cone wear. This is due to the servo-slope which transforms the friction torque to axial force.
In other words, the index length becomes larger in accordance with cone wear, and consequently the overlap length on the chamfer surface will also increase.
Therefore, in case of an application with excessive wear, the design of K.H.S. overlap length has to be considered carefully.
Also the durability of the cone surface (friction material) changes when using a K.H.S. instead of a Borg Warner Synchronizer. The increased performance creates a larger load on the friction material. In case of the same shifting force, the working load on the cone surface is increased due to the advanced performance.
Therefore it is recommended to check the specific loads on the friction material when applying a K.H.S. instead of a Borg Warner Synchronizer. If replacing a Borg Warner double cone synchronizer with a K.H.S. single cone synchronizer it is recommended to use strong friction materials (e.g. carbon lining) to avoid durability problems. This will also increase the performance ratio of the K.H.S. significantly due to the higher friction coefficient of carbon material.

SIMULATION
The development of new synchronizer concepts with only hardware prototypes is obsolete due to the possibility of virtual prototyping (=simulation). Too many prototypes would be needed to get to a reliable design for serial production. With dynamic simulation it is possible to find an optimum design in very short time and avoid poor design concepts very early before hardware prototypes.
Test bench and vehicle measurements are only needed as a basis for simulation and for final verification.
A very detailed shift comfort model [7] was built up for the virtual validation of the K.H.S. This model consists of all parts and systems which have impact on the shift comfort [8] as can be seen in fig. 5. Parameters are gathered with test bench measurements on shift comfort test benches (drag torques, dynamic stiffness, etc.) and generated out of CAD-data (geometries, inertias, etc.). The model replaces the real test bench completely after a fine-tuning process has taken place (calibration with test bench results). The correlation of simulation and test bench results can be seen in fig. 6. The test benches are also used for the validation of hardware prototypes. By experience simulations are able to confidently predict the results of shift comfort tests. Compared to development methods without simulation support it was possible to achieve working concepts more quickly.

![Simulation model with modular architecture](image)

During the simulation work on the K.H.S. system it is possible to identify the optimum design for the system regarding shift comfort in all temperature areas. Therefore, an optimum for unlock safety at low temperatures, enough blocking safety for all situations (lowest friction coefficients), high synchronization capacity and other shift comfort criteria (nibble, double bumps etc.) for different shift speeds [7] have to be worked out. The simulation results show, that a Borg Warner double cone synchronizer can be replaced with an optimized K.H.S. single cone synchronizer without expected disadvantages in shift comfort.

The iterative simulation procedure is very important to find an optimum and this procedure is recommended for every synchronizer application since parameters such as the driveline dynamics, the external and internal shifting system, gearbox drag torque and other parameters have a big influence on the system and are different for every application. Only with this pre-optimization simulation a K.H.S. design with optimum performance can be achieved in reasonable development time.
EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

For the performance verification of the K.H.S. system, it had to be compared to a Borg Warner Synchronizer regarding shift comfort in a real gearbox on a special test bench (reproducing the vehicle) under highly reproducible and equal conditions. A special shift comfort test bench was built up for this purpose. The basic concept of this test bench can be seen in fig. 7.

For reference a gearbox with BW synchronizers was evaluated regarding shift comfort at different temperatures and different shift characteristics (quick, medium, slow). These shifts were analysed with the hofer-tool ProGear® for automated shift comfort evaluation. With ProGear® it is possible to quickly evaluate a substantial number (several thousands) of shifts automatically and objectively.

Firstly, the synchronization performance (=synchronization capacity) is evaluated with a basic grade (maximum grading 10). Then negative influences as double bumps, nibble, unlock and spool-in effects are graded. This leads to a total shift comfort grade. The user interface of ProGear® is shown in fig. 8.

After gathering the reference data the Borg Warner Synchronizers were replaced with K.H.S. prototypes and the same test procedure was done with the new system. The analysis of this data leads to a complete comparison of the two synchronizer systems at all temperatures and shift situations regarding shift comfort.

Fig. 7: Shift comfort test bench concept
An example (temperature -20°C) of experimental results of the K.H.S.-prototypes with single cone compared to the original Borg Warner synchronizers with double cone is shown in fig. 9.

These results show that the performance predicted by the simulation has already been reached, because the single cone K.H.S. brings about the same results as the double cone BW, also under low temperature conditions (-20 °C).

The synchronization performance with a K.H.S. single cone system is slightly better than that of a Borg Warner double cone system with the same friction material. Also the total shift comfort (double bumps, nibble, unlock, spool-in) of the Borg Warner double cone was achieved using the same friction material in this application.

By using a better friction material like carbon lining the synchronization performance and the total shift comfort can be improved even more. The results in fig. 9 show this clearly.
CONCLUSIONS
The Kyowa High Performance Synchronizer was introduced as a system to efficiently increase the synchronization capacity of a Borg Warner Synchronizer without changing interfaces inside the gearbox.

A simulation model was built up to pre-optimize the design prior to hardware prototyping to avoid costly hardware loops. A shift comfort test bench and automated shift comfort evaluation were used to verify the performance of the new system with respect to the Borg Warner Synchronizer. The results show that a K.H.S. with one friction cone can replace a Borg Warner double cone system due to the amplification without apparent negative influences on the shift comfort.

K.H.S. FUTURE SCOPE AND OUTLOOK
The test results as well as the simulation results show that a K.H.S. single cone can replace a Borg Warner double cone synchronizer with achieving the same shift comfort under various conditions. The performance of a K.H.S. can be significantly increased by using carbon lining.

In the meantime, we are also developing multi cone K.H.S systems. The simulation results show, that a double cone K.H.S. can have a significantly better synchronizing performance than a triple cone Borg Warner Synchronizer due to the fact that the performance ratio is increasing progressively with the synchronizing capacity of the friction cones (see fig. 3). A triple cone "K.H.S." will allow to realize a huge synchronizer performance which can not be achieved by any Borg Warner design, therefore this synchronizer can be applied to special gearboxes which need a substantial synchronizing performance.

REFERENCES