A Review on Multicone Synchromesh Transmissions

[1] Nagesh S. Gorre, [2] Hemant.D.Lagdive
[1]M.E. Student, [2]Associate Professor,
[1]Mechanical Engineering Department,
[1, 2] N.B. Navale Sinhgad College of Engineering, Solapur, India
Email – [1] nageshgorre@gmail.com, [2] hemantlagdive73@gmail.com,

Abstract: *Modern transmission concepts require increased efforts to achieve improvements in comfort and efficiency in line with reduced cost. Synchronizer systems are the central element for a change of ratio in stepped transmissions. The trend toward transmissions with optimized efficiency and improved comfort at the same time requires aligned high-capacity synchronizer systems. This paper presents the detail review of multi cone synchronizer system along with its components, working principle and basic design calculations. Material requirement and common materials used for synchronizer components are summarized.*

Key Words: *Drag Torque, Index Torque, Cone Torque, Shift Force, Synchronization Time, Strut Type Blocker Synchronizer*

1. INTRODUCTION:

The transmission system is one of the main parts of an automobile that determines the behavior, power and fuel economy of the vehicle. Transmission performance is usually related to gear efficiency, gear noise and gear shift comfort during gear change. Synchronizer mechanisms were developed in the 1920s to allow gear changing in a smooth way, noiseless and without vibrations both for the durability of the transmission and the comfort for the users. What is sought is dynamic shift quality, by means of reduced shifting time and shift effort; especially in heavy truck applications since the torques in the drive train are larger.

Previous researchers have dealt with several mathematical and computational models of synchronization processes (e.g. [11], [12], [13], [14], [15]) and have validated them with experimental data from test rigs. Additionally, as it is known that drag torque contributes significantly to the engagement of synchronizers in transmissions and can cause the mechanism to fail, some publications are studies of different models of the affecting drag. Other authors go deeper in modeling and direct their attention to the effect of the friction and the consideration of the different stages of lubrication during the process (e.g. [2] and [7]). Nevertheless, they all agreed that `Recognized problems exist, such as second bump, gear-changing noise, or impossible gear changing, the reasons for which are still unknown.
Several technical papers and patents are focused on the design and performance of this component (e.g. [1], [6], [8]). However, all these publications have different contributions to the main topic [18]. Some give a description of the main aspects of the changing mechanism [16] and the working principle and introduce basic calculation of the principal parameters. Others over a description of new designs for synchronizers [9] and their single components in order to amplify their capacity in terms of reducing the synchronization time or the effort at gear shift lever, especially in the lower speeds where the gear reduction ratio is larger.

2. COMMON TYPES OF SYNCHRONIZER MECHANISMS:

Presently most widely used type of synchronizer is the Blocker Ring Synchronizer which has a mechanism that prevents the coupling teeth engagement before completion of synchronization; a distinct disadvantage suffered by its predecessor – The Constant load type synchronizers. The Blocker ring Synchronizers are categorized into two types – the Strut and the Pin type. To enhance the synchronizing torque, some synchronizers employ two or more synchronizing cones e.g. Dual or multi cone synchronizers.

A. Constant Load Type Synchronizer

The earliest form of synchronizer, Fig 1, commonly used in automotive gearboxes is known as the Constant Load Type. Thrust between the cones is applied by the outer hub initiated by the sleeve movement by the driver. Spring/ball arrangement ensures the detent load. The main disadvantage of the constant load synchronizer is that it is relative easy to overcome the detent and try to engage the coupling teeth

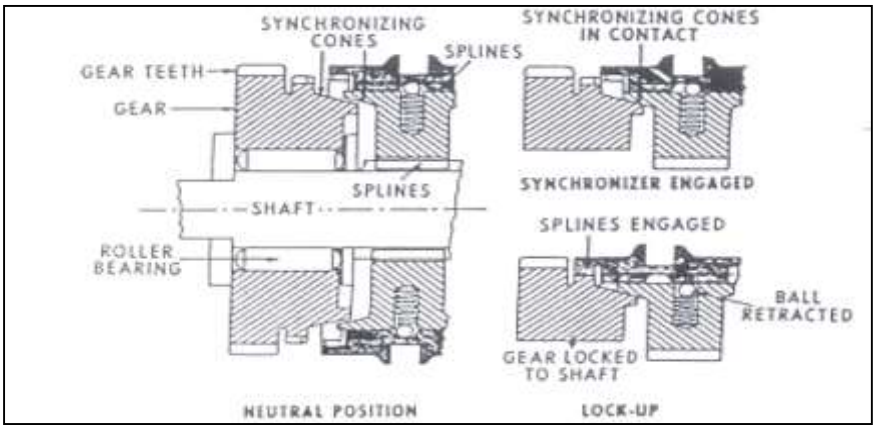


Fig. 1: Constant Load Type Synchronizer

B. Blocker Ring Type Synchronizer

1) Pin Type Blocker Synchronizer

Fig. 2 illustrates a pin type synchronizer. The actuating hub is splined to the shaft and rotates with it. The outer ring is splined to the ends of the gears. The Stop Ring and Pin assembly are loosely pinned to the actuating hub. When the actuating hub is moved to the right or left, the stop ring and pin assemblies hold the loose fitting pin against the side of the holes in the actuating hub. The actuating hub is prevented from engaging the gear by the chamfered shoulder on the stop ring and the pin assembly. When all parts are rotating on the same, the force between the pin and the actuating hub is reduced. The hub can then move over the large base of the pins and internal splines on the hub can engage the splines on the gear. Slight chamfers on the pin and the actuating hub as well as rounded ends of the splines on the hub and the gear, permit these parts to align themselves and mesh easily.

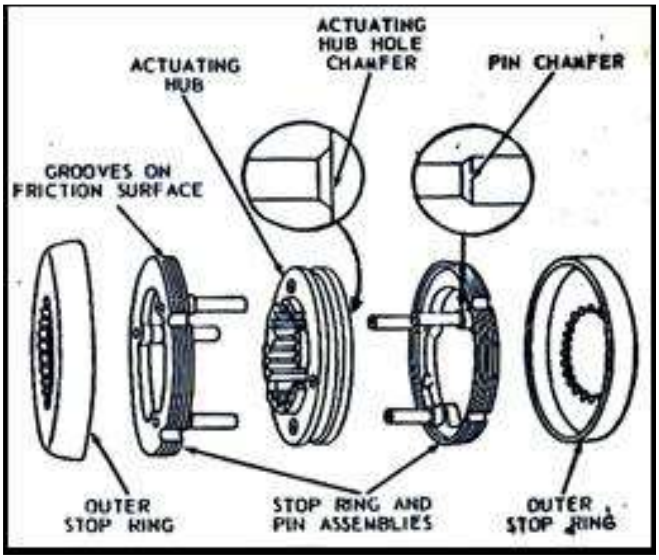


Fig- 2: Pin type Blocker Synchronizer

2) Strut Type Blocker Ring Type Synchronizer

The most widely used type of synchronizer, in automotive application, is termed the Blocker ring Synchronizer. This is similar to the Constant Load type but with the addition of a mechanism that mechanically prevents the coupling teeth engaging before synchronization is complete.

The parts of the Block Type Synchronizer are as shown in Fig. 3. During Synchronization, the sleeve is moved towards the selected gear pushing the blocking ring to the left. The ring contacts the shoulder of the driven gear and begins to synchronize the speeds of the parts. To complete the shift, the sleeve teeth pass through the blocking ring teeth and mesh with clutch teeth / dog teeth on the driven gear.

Strut type blocker ring type Synchronizers again classified based on no of friction surface as

- Single Cone: Having only one friction surface
- Multi cone: Having two or more friction surfaces
- Details about multi cone synchronizer system are explained in next section.

3. MULTI CONE SYNCHRONIZER SYSTEM:

A. Components

1) Gears

Normally is connected to the main shaft by a needle bearing for relative rotation between both components and secured against axial movement relative to the shaft. It can also be mounted on the shaft with a very smooth surface and proper lubrication. Dog plate press fitted or laser welded with the gear wheel. The external teeth with chamfer on both sides of the teeth interlock with the chamfer on the internal teeth of shift sleeve.

2) Sliding Sleeve / Gear Shift Sleeve / Synchronizer Sleeve / Coupling Sleeve:

Has a groove on the outer periphery for the gear shift fork. Internal splines are in constant mesh with the synchro hub external splines. So it is only axially movable from a neutral position to an engaged position. Both parts and the main shaft work as a single unit hence they move at the same angular speed 1 & 8. Gears, 2. Shifter Sleeve, 3. Synchronizer Hub, 4. Outer Ring, 5. Intermediate Ring, 6. Inner Ring, 7. Struts

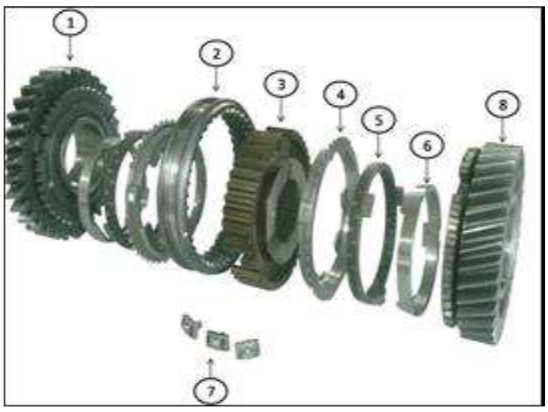


Fig. 3: Exploded view of Multi cone Synchronizer System

3) Synchronizer Hub

The synchronizer hub is positively locked with the transmission shaft. It contains three to six equidistance slots for pre-synchronization components. Sleeve can slide over the splines provided at the outside diameter of hub. Hub anchors blocker ring with notches on the circumference.

4) Outer Ring / Synchronizer Ring

The external teeth interlock with the internal teeth of the sliding sleeve. It has a conical surface that is fitted with the conical surface of the intermediate ring. Its purpose is to produce the friction torque needed to synchronize the input and output shafts. The cone surfaces are provided with thread or groove patterns and axial grooves in order to either prevent or break the hydrodynamic oil film and minimize force increase.

5) Strut Detent / Centering Mechanism / Strut Key:

Spring loaded ball or roller fixed in a cage. It is arranged on the circumference of the synchronizer body, positioned between the groove in synchro hub and the inner groove in shift sleeve. Therefore can integrally rotate with the synchro hub and is axially movable with the shift sleeve. This component is used for pre-synchronization; it means that generates the load on synchro ring to perform the synchronization process. In addition, maintains the sliding sleeve in a central position on the hub between both gear wheels and below a limit axial force. Often, the synchronizers are composed by three of these elements arranged at 120°. In the case of large synchronizers, there are four elements arranged at 90°.

B. Phases of Synchronization:

Depending on sources and specific synchronizer designs the number of phases varies, but the working principle is the same. Therefore, the synchronization process, from the neutral position (when there is no power transmission) to full engagement, could be defined with the following eight steps:

1) First Free Fly

The sleeve moves axially from the neutral position without significant mechanical resistance and make the detent face come in contact with the synchro ring face. In this phase the axial velocity is high and the axial force low. See Fig. 3.1 (a) for the initial and final position of this phase.

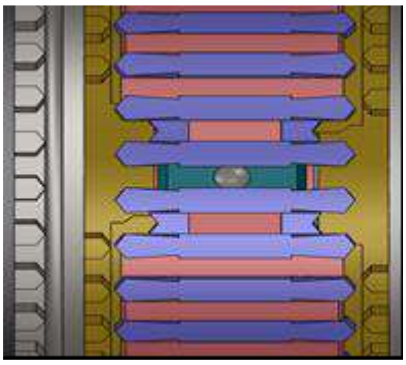
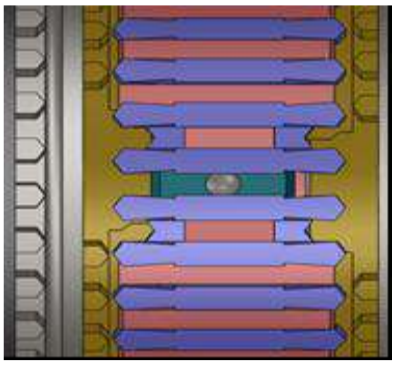



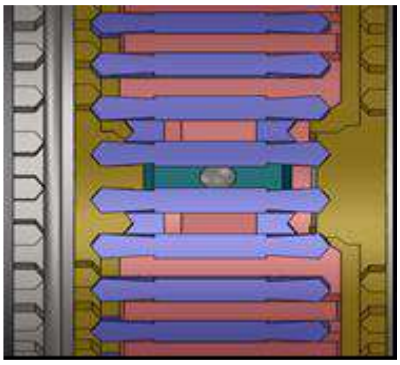
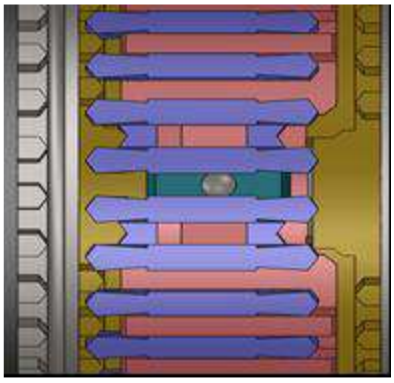
Fig. 3.1 (a) Initial and final position of First free fly

2) Start of Angular Velocity Synchronization

The detent force creates a frictional torque that makes the ring rotate within the available space in the recesses of the synchro hub, the oil film between cone surfaces is removed and the spline chamfers of the synchronization ring and sleeve gets the maximum contact area and a high coefficient of friction. See Fig. 3.1 (a) (right) and 3.1 (b) for the initial and final position of this phase.

3) Angular Velocity Synchronization

This phase is over when the gear, synchro ring and sleeve have the same angular velocity. Otherwise, the equilibrium of axial and tangential forces applied on the spline chamfers prevents from continuation of the gear changing process. This last effect is known as interdiction (Fig. 3.1 (b)).

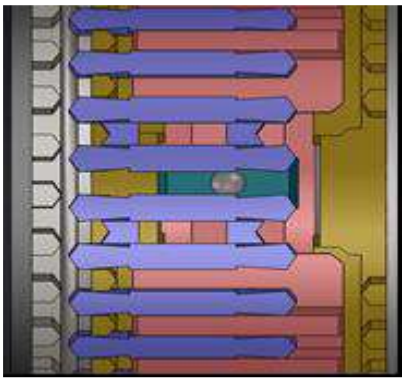
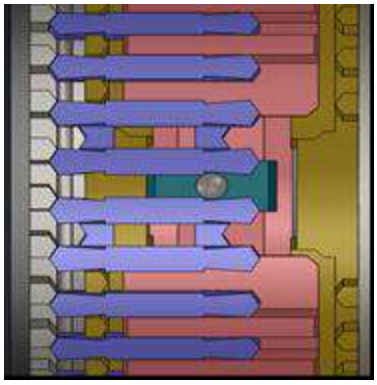
(b) Spline position during the angular velocity synchronization. (c) Final position of turning the synchro ring.

4) Turning the Synchro Ring

The synchro ring that was previously heated by the dissipated friction energy loses the heat and becomes stuck on the cone due to the diameter reduction. The displacement of the sleeve turn the synchro ring and the clutch gear while the chamfers remain in contact (Fig. 3.1 (c)).

5) Second Free Fly

The sleeve moves forward axially until approaching the spline chamfers of the clutch gear (Fig. 3.1 (d)).

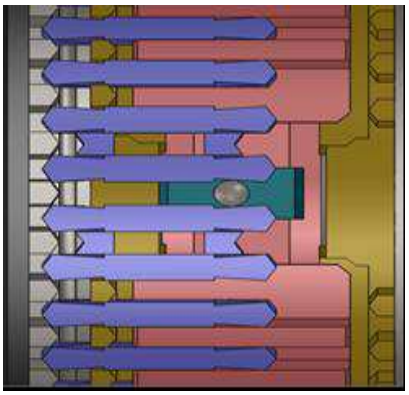
d) Second free fly. (e) Spline position during the Start of the second bump

6) Start of the second bump

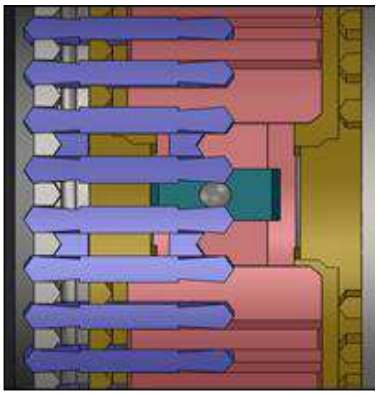
As there is an oil film that has to be broken between the chamfer surfaces, an increase of the axial force is required in order to maintain the axial velocity of the sleeve. As the oil is being discharged this axial force suffers a higher increment. This stops when the tangential force component on the chamfers is high enough to turn the synchro ring which was stuck in the cone (Fig. 3.1 (e)).

7) Turning the gear

The axial force required to turn the gear depends on the relative position of the sleeve splines and gear splines (obtained at the end of the synchronization, phase 3). See Fig. 3.1 (f) for the end position of this phase.



(f) Final position of turning the gear.



(g) End position of Final free fly.

Fig. 3.1: Spline position during the synchronization process (phases) [3].

8) Final free fly

The gear wheel is engaged, as shown in Fig. 3.1 (g).

C. Synchronizer Design

Synchronizer design is itself is vast subject and varies with different organizations. Most of synchronizer design organizations have their own way of dealing with it and it is more or less proprietary. But some basic criteria are common, which shall meet with all the synchronizer designs. Synchronizer calculations involve amount of friction torque generated, specific energy, synchronization time, bending safety etc. Some of the key design aspects of synchronizer are as below:

The cone angle and tooth chamfer angle for the synchronizers can be selected optimizing positivity ratio. Positivity ratio should be more than one, to ensure complete synchronization prior to blocking release

$$\text{Positivity Ratio} = \frac{\tau c}{\tau i}$$

Where,

τc = Cone torque or synchronization torque
τi = Index torque.

Cone torque can be calculated as,

$$\tau c = \frac{F\, n\, \mu_D\, d_m}{2 \sin \alpha} \pm \tau_d$$

Where,

F = Axial load at sleeve
n = Number of cone
μD = Dynamic coefficient of friction
dm = Mean value of cone diameter
α = Cone angle
τd = Drag torque

Axial load at sleeve can be determined as,

$$F = Fa \times L$$

Where,

Fa = Force on handball

L = Mechanical leverage of the transmission

Index torque can be calculated as,

$$\tau i = \frac{F\,D}{2}\,\frac{\cos\theta - \mu_o \sin\theta}{\sin\theta + \mu_o \cos\theta}$$

Where,

D = Pitch circle diameter of sleeve or blocker ring
θ = Angle of tooth chamfer with axis of the tooth.
μo = Coefficient of friction at tooth chamfers

The effort required to change gear is measured in shift time integral also known as shift impulse. Theoretical shift impulse can be calculated as.

$$\text{Shift Impulse} = k \times Fa \times ts$$

Where,

k = shift force index, which depends on oil, type of friction material, type of synchronizer design, transmission drag, speed of cone torque rise, amount of compliance in shift system etc.
tS= Synchronization time.

Synchronization time can be calculated as,

$$ts = \frac{I_r\,\Delta\omega}{\tau_c}$$

Where,

Ir = Reflected inertia of gear to be selected
Δω = (ω1 – ω2) = Differential angular velocity
$\Delta\omega = \frac{2\pi\,\Delta n}{60}$

Where,

Δn = speed difference of gear to be selected and current speed of sleeve.

Reflected inertia can be calculated by tracing direction of torque towards the clutch, using following equation,

$$I_r = I_a \times G^2$$

Where,

Ia = Mass inertia of gear
G = Gear ratio with mating component

For example Reflected inertia of first gear in reference transmission shown in fig 1 can be calculated as,

$$I_{r1} = I_1 + (G_1)^2 \times [I_c + (\frac{1}{G_4})^2\,(I_i + I_d)]$$

Here,

Ir1 - Reflected inertia of gear 1
I1 - Mass inertia of gear 1
G1 - Ratio of driven gear to drive gear for gear 1
Ic - Inertia of cluster gear
G4 - Ratio of driven gear by drive gear for gear 4
Ii - Mass inertia of input shaft
Id - Clutch disc inertia

Another important factor to be determined by calculation, is about work done by synchronizer, known as energy absorbed by synchronizer or kinetic energy and can be determined by,

$$E = \frac{1}{2} I_r\,\Delta\omega^2 \pm \frac{1}{2}\tau_D\,ts\,\Delta\omega^2$$

Where,

E = Kinetic energy

Energy indulged by friction element per unit area is called specific energy and can be calculated as,

$$E_s = \frac{E}{A}$$

Where,

Es = Specific energy,
A = total friction area

Energy dissipated per unit time is friction power and is determined by,

$$J = \frac{E}{t_s}$$

Where,

J = Power in watts

Energy dissipated per unit time per unit area of synchronizer is known as specific power and is important characteristic of friction material.

$$J_s = \frac{J}{t_s}$$

Where,

Js = Specific Power

Apart from this synchronizer design should also take care of various critical gaps and tolerance stack to be reviewed for verification of these gaps.

D. Materials

Selection of material for components of synchronizer system is critical as it affects on the service life and reliability of a synchronizer. Material and process of each component is summarized below:

1) Effects of Materials on Synchronizer Performance

Material combination for a given application is mostly influenced by:

Sufficient high and consistent value of dynamic coefficient of friction Resistance to cone jamming.

2) Material Combinations:

For the male/ female cone case-hardened steel with a surface hardness of 60 Rockwell "C" is almost universally used, although Molybdenum coated cones have been used with sintered iron or steel synchronizer rings. Synchronizer rings made from sintered iron or steel [17] have also been used in applications where gear box operates with a SAE 20W/50 lubricant (engine oil).

Since the drag torque is mainly dependent on the transmission fluid (Gear Oil), its selection plays a predominant role in synchronizers performance [7]. Oil compatibility test is conducted as a part of validation testing to verify the oil compatibility with particular friction material at different temperature and different no. of shift cycles differ from company to company.

Synchronizer rings are generally divided into two categories; those made from a high strength material coated with a friction material and those entirely made from one material. Most synchronizer rings are manufactured from one of the following copper-based alloys [6]:

- Manganese Bronze - Usually Forged, High strength
- Aluminum Bronze - Usually Die Cast, Good wear Properties
- Silicon Manganese Bronze - Good Strength, Good wear properties

4. CONCLUSION:

The state of art review of multi cone synchronizer system is presented in this literature. Different types of synchronizers are listed. Different components and their function are explained in the literature. Working of blocker ring type synchronizers is explained including the different phases of synchronization. Various factors considered in the designing of the synchronizer system are presented. Different materials used for synchronizer components and their influence on the synchronizer performance are summarized.

In all vehicle applications from passenger car to large trucks, the trend is towards improving shift ability and reducing manufacturing costs. Lower shift lever effort, reduced shift lever travel and smoother operation of the shift lever all contribute to improving gear shift quality.

The basic Borg Warner design has over the years been optimized through innovative use / application of materials and manufacturing processes. But the basic problem of ‘opposing criteria-either /or’ of low Cone angle and self jamming has not been fully eliminated. As the cone angle and tooth chamfer angles not optimized beyond specific limit, hence detail study is needed in order to optimize the synchronizer time and shift effort.

Detail study needed in new materials and manufacturing processes to reduce cost and improve performance Powder metal forging to produce near net shaped components and minimize machining is one of such processes.

It is used for Outer Rings in single cone application. The research to be done in the direction of manufacturing of Inner ring and intermediate rings with sintering which are processed currently by stamping and machining process.

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