

To this point, requirements imposed on the transmission have been introduced that are satisfied via multiple gears and appropriate gear ratio changes. In Sect. 2.1, this chapter describes the various phases of a shift sequence and compares the ideal shift sequence with shift sequences that are not acceptable in terms of quality. The shift-related torque changes as well as the engine excitations and torque variations cause the powertrain to vibrate. In Sect. 2.2, the occurring vibrations and eigen frequencies are discussed, as well as measures for reducing these vibration occurrences.

The focus on comfort, which is becoming evermore significant, is moving the mastery of noise and vibration development into the foreground. Section 2.3 concentrates on vehicle acoustics and the behavior of the transmission in this area of conflicting objectives. Because the powertrain and vehicle body are interconnected, the vibrating powertrain can also excite the vehicle body and thus significantly influence the perception of comfort. This is discussed in Sect. 2.4. Many of the reactions are only subjectively perceptible for vehicle occupants. Therefore, the chapter closes with the description of human physiological perception.

2.1 Fundamentals of Gear Ratio Change and Synchronization

2.1.1 Classification of Shift Sequences

Different types of shift sequences are defined for changing gears appropriately for different driving situations and transmission designs.

If the torque flow through the transmission system remains intact during the shift, this is referred to as a *powershift*. This requires appropriate powershift-capable transmissions, such as step automatic transmissions (AT) or dual clutch transmissions (DCT). Moreover, there are additional transmission types that can only execute powershifts for a subset of shifts [38, 132]. If the powertrain is opened during a shift, this is referred to as an *inter-*

rupted shift. Transmission technologies, such as manual transmissions (MT) or automated manual transmissions (AMT) can realize only such shift sequences for design reasons. Situational, such shift sequences are also executed by powershift transmissions.

The *direction of shift* is an additional differentiation. Shifts into a higher (longer) gear (with a smaller gear ratio i) are referred to as upshifts, shifts into a lower (shorter) gear (with a larger gear ratio i) are referred to as downshifts. And finally the *direction of torque flow* is also used for further distinction. Based on the traction demands (see Sect. 1.2) of driving situations, these are either powered shifts with positive torque on the transmission input shaft ($M_{An} > 0$) or coast-down shifts without or negative torque ($M_{An} \leq 0$). A combination of the last two criteria is formed; the essential shifts are summarized in Table 2.1.

This allocation applies for powershifting and interrupting shift sequences with the prerequisite of a uniform driver desire during the shift sequence, this is the case for the majority of shifts in real world. If the driver’s desire changes after the shift request, this is referred to as a change-of-mind shift. Depending on the progress of the original shift sequence, additional strategies are implemented for aborting or changing to a different type of shift.

Finally, shifts into an adjacent gear (next larger or next smaller gear ratio) are referred to as *single shifts* and shifts that omit the adjacent gear ratio stages are referred to as *skip shifts*.

During the shift sequence, the torque flow is controlled (open loop control is most commonly used and sometimes superposed with closed loop control) through both, the torque on the clutches and the torque of the engine. The basic sequences for selected shifts are presented in an idealized manner and the essential sensitivities relative to torque deviations are shown.

The control (open and closed loop) implementation as well as application of shift sequences (see Chap. 5) requires precise consideration of stiffness, inertia, and characteristics of friction elements, as well as torque buildup and reduction (torque truncation) of the engine. The position of the shifting elements and clutches in realized transmissions (see Chap. 6) is particularly relevant for the shift sequence. For calculation of powershifts, the powertrain (Fig. 2.1)—from engine to driving wheels—is broken down into two subsystems [41]:

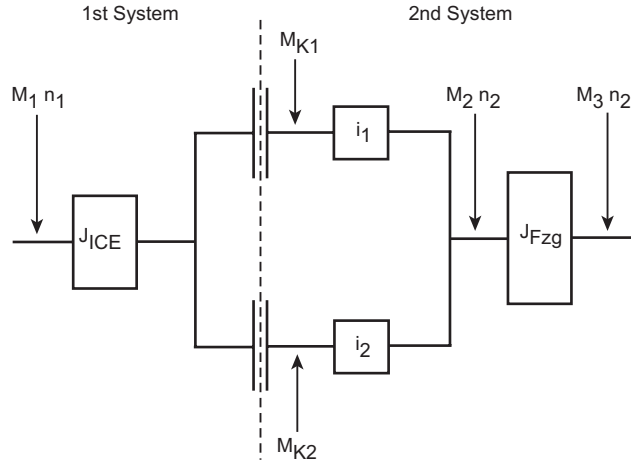
- First subsystem: Engine to the primary side of the friction element in the transmission
- Second subsystem: Secondary side of the friction Element

Each subsystem must contain all elements via which power can be supplied, dissipated, or stored when shifting, and each subsystem must be in balance on its own.

Table 2.1 Shift types

Gear ratio	$M_{An} > 0$	$M_{An} \leq 0$
$i_{new} < i_{old}$	Power upshift	Coast upshift
$i_{new} > i_{old}$	Power downshift	Coast downshift

Fig. 2.1 Simulation model for ratio changes with torque fill



The model idealized in this manner can be used for all shifts; the inertia (as well as stiffness, and damping) upstream and downstream of the friction elements must be considered (in accordance with the procedures in Sect. 2.2.4).¹

The torques of the clutches M_{K1} and M_{K2} determine the torque level that is applied to the powertrain. Transmission losses are omitted in these principle examinations, and for each subsystem thus,

- the torque equilibrium for the engine-side subsystem is

$$M_1 - J_{ICE} \dot{\omega}_1 - M_{K1} - M_{K2} = 0, \quad (2.1)$$

- the torque equilibrium for the vehicle-side subsystem is

$$M_{K1} i_1 + M_{K2} i_2 - M_3 - J_{Fzg} \dot{\omega}_{Fzg} = 0. \quad (2.2)$$

As an approximation, in the simulations M_3 is set to zero.

2.1.2 Power Upshift as Powershift without Engine Torque Control

The clutch fundamentals introduced in Sect. 1.4.1 are prerequisites for the considerations below.

¹ In this regard the parameters of the gear-specific simulation models vary in accordance with Fig. 2.1 for automatic transmissions upstream and downstream of the friction elements, for dual clutch transmissions the left side remains unchanged.

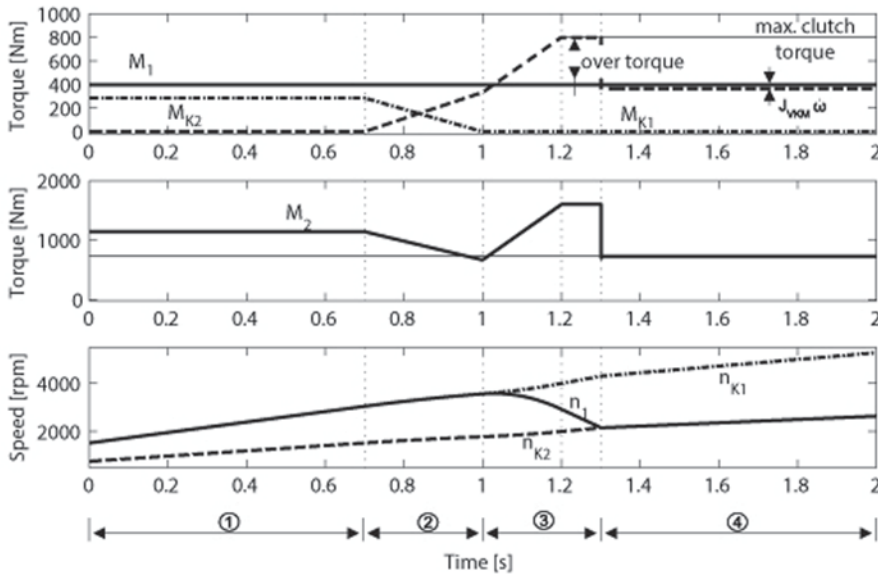


Fig. 2.2 Power upshift without engine torque control

Figure 2.2 shows a power upshift without engine torque control.

Preparatory Phase: At the beginning of the shift, clutch K1 is engaged, and clutch K2 is disengaged, i.e., $M_{K2}=0$. Engine torque M_1 is kept constant during the entire shift event. Output torque is determined with

$$M_2 = i_1 M_{K1} \quad (2.3)$$

(M_{K2} is disengaged); and M_{K1} from (2.1) results in

$$M_{K1} = M_1 - J_{ICE} \dot{\omega}_1. \quad (2.4)$$

Engine speed n_1 and speed of clutch K1, n_{K1} , are equal and increase linearly. Solid lines represent speeds and torques of the engine and output, for the upper torque path of clutch K1, a dash-dotted line is used, the dashed lines trace the lower torque path of clutch K2.

Hand-over Phase: Clutch K2 starts to engage and torque is transferred via the clutch (M_{K2} increases). This reduces the torque M_{K1} on clutch K1 (see Eq. 2.1). While the engaging clutch K2 slips, clutch K1 sticks. At the end of torque transfer, engine torque M_1 is completely transferred to the new clutch and output torque M_2 in accordance with Eq. (2.5) decreases with the new gear ratio i_2 . In this process, clutch K1 must also be simulated for its transferrable torque in such a manner that

- the clutch always sticks during the hand-over phase,
- the transferable torque of the clutch is completely dissipated precisely at the end of the hand-over phase, i.e., M_{K1} becomes zero.

The torque level at the end of this phase represents the lowest point in the torque progression M_2 during the shift.

$$M_2 = i_2 M_{K2}. \quad (2.5)$$

Synchronization Phase: For an upshift, the engine speed must be adapted to the new target speed during this phase. In this case, this is achieved by increasing the torque on clutch K2 beyond the engine torque. Deceleration of engine speed is calculated according to the torque equilibrium of the engine-side subsystem in accordance with Eq. (2.1) with $M_{K1} = 0$ and is expressed as

$$\dot{\omega}_1 = \frac{M_1 - M_{K2}}{J_{ICE}}. \quad (2.6)$$

Reducing the engine speed delivers an additional dynamic torque that causes an increase of the output torque M_2 . As soon as the synchronous point is reached, the output torque M_2 collapses. Due to the sudden torque changes, the powertrain which has a finite stiffness is excited to vibration; Sect. 2.2 discusses the phenomena that occur.

Completion Phase: At this point the shift is concluded, in this phase the shift sequence control is transferred to the calling algorithms. In this phase, the clutch torque M_{K2} is lower by $J_{ICE} \dot{\omega}_1$ than the engine torque M_1 .

Figure 2.3 shows appropriate control of clutch pressure as an example. In normal driving operation (i.e., gear selected, clutch engaged, and no slip) the set clutch torque is higher than actually required, to ensure that the clutch does not slip. Prior to transfer of torque, the pressure of the active clutch K1, which determines the clutch torques, is already lowered to arrive at the slip limit—the clutch just remains sticking. This provides the necessary starting point for the torque reduction to ensure that at the point in time the torque of the oncoming clutch K2 is fully build up; it is solely transferred through clutch K2.

During the hand-over phase, the torque is transferred from the disengaging clutch K1 to the engaging clutch K2, both clutches transfer torque. During the torque transfer, while the engaging clutch K2 slips, clutch K1 sticks. Because clutch K1 sticks, the transferable torque on clutch K1 can be adjusted as desired within the limits entered in Fig. 2.3 (minimum and maximum profile of K1), as long as it is equal to or greater than the required torque, and clutch K1 does not transfer any torque after the completed torque transfer. Otherwise the corresponding power of clutch K1 would dissipate completely and would not be available for vehicle propulsion. It must be ensured that at the end of torque transfer the pressure of the releasing clutch K1 is completely reduced to zero.

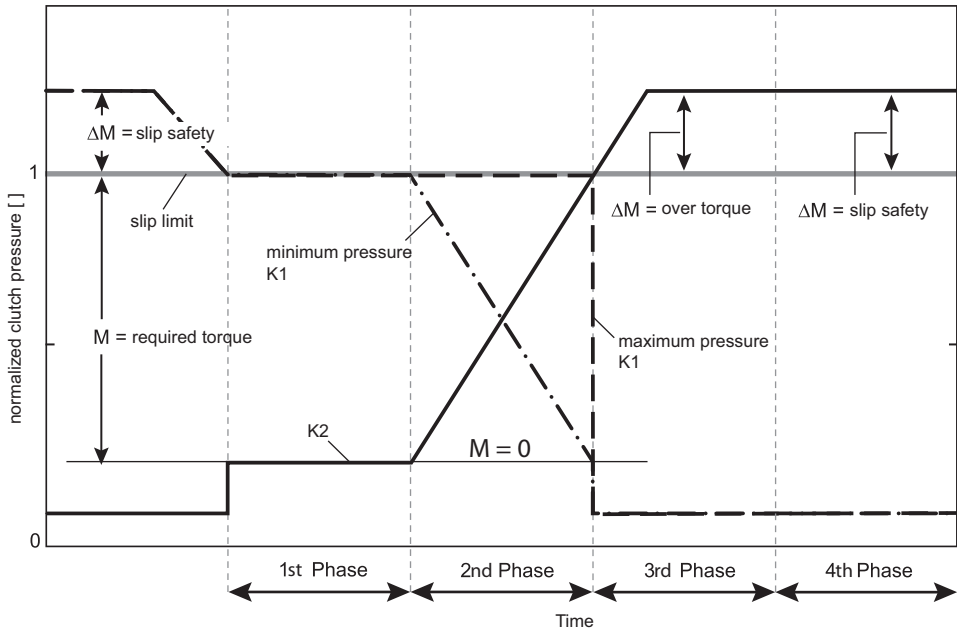


Fig. 2.3 1st, 2nd, 3rd, 4th phase of clutch pressure

The overtorque adjusted in the synchronization phase is also taken over in the following phase in the example shown, where it serves as safety against slippage.

2.1.3 Power Upshift as Powershift with Engine Torque Control

The overtorque of the acceleration torque M_2 at power upshift without torque control is perceived as inharmonious. Moreover power is dissipated on the slipping clutch, this must be minimized for fuel consumption reasons, and thus the loads on the tribosystem are also reduced. Consequently modern transmission technology, i.e., powertrain technology, uses control strategies, which in addition to clutch torque, also influence engine torque when shifting.

A power upshift of the simple model with engine torque control is shown in Fig. 2.4. Instead of the overtorque of the clutch, through reduction of the engine torque M_1 adjustment of the engine speed n_1 to the new output speed is achieved. The two first phases are the same in this example as they are in the preceding example.

Preparatory Phase Clutch K1 is engaged, clutch K2 is completely disengaged. The output torque is calculated in accordance with Eq. (2.3).

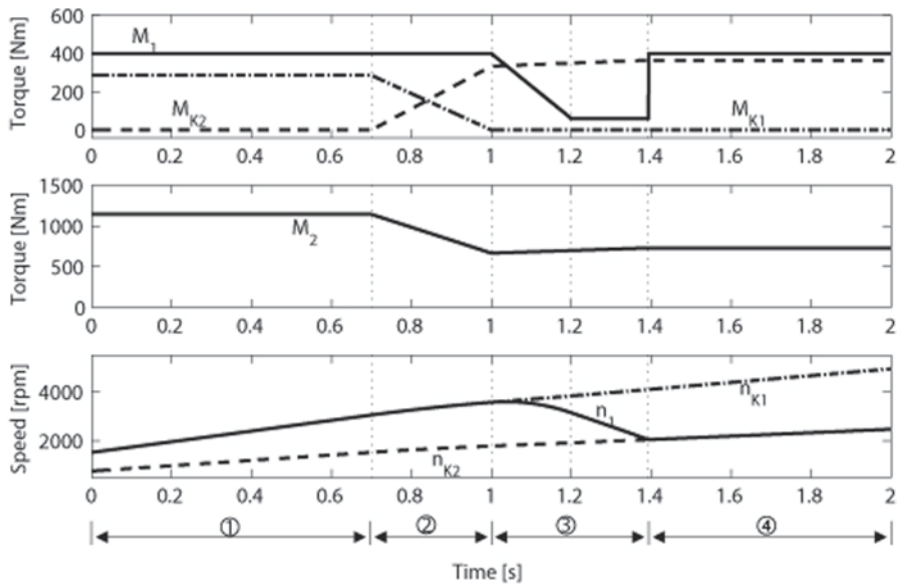


Fig. 2.4 Power upshift with engine torque control

Hand-over Phase Torque is transferred from clutch K1 to clutch K2 in the same manner shown in the previous example. M_2 decreases due to the new gear ratio.

Synchronization Phase After the torque transfer from clutch K1 to clutch K2 is completed, the engine torque is decreased. In accordance with Eq. (2.6) the change in engine speed becomes negative. Clutch torque M_{K2} is slightly increased during the torque reduction, in order to ensure safe sticking of the clutch at the end of speed synchronization. Thus the output torque M_2 also increases.

Completion Phase When the engine speed n_1 has adjusted to the new output speed n_{K2} , the engine torque has to be promptly increased again. In practice, the abrupt increase in engine torque is almost impossible to achieve. On one hand, for real internal combustion engines (ICEs) such a curve cannot be presented in a manner that is reproducible, on the other hand the time point must be met with absolute precision, otherwise the torque curve M_2 changes abruptly.

2.1.4 Sensitivities for Power Upshifts as Powershifts

If there are deviations, the system reactions can significantly impair comfort. Even analyzing the simplified shift sequences, it can already be observed that deviations from the torque curves cause disturbances. Three essential disturbances are:

1. The releasing clutch still transfers torque, although the engaging clutch already transfers the full torque (locking).
2. After the engine torque reduction, the engine torque is not built up precisely on the synchronous point.
3. The torque on the power—conducting releasing clutch is reduced prematurely.

Torque Reduction of the Releasing Clutch Completed too Late

Figure 2.5 shows the delayed reduction of torque on the releasing clutch K1 as an example. In this regard it is irrelevant whether clutch K2 transfers the torque too quickly or whether clutch K1 is completely released too late. If the engine torque drops in the course of the shift without the clutch torque being adjusted accordingly, then such a reaction can also be expected.

Preparatory Phase The engine torque is transferred via clutch K1. Clutch K2 is released.

Hand-over Phase At the end of the torque transfer clutch K1 still transfers torque, after clutch K2 has taken over the complete torque. Clutch K1 sticks and through the torque transfer from clutch K1 power is dissipated at clutch K2; clutch K1 transfers negative torque. The output torque M_2 is reduced accordingly. With the complete release of clutch K1 the output torque increases in accordance with the gradient, with which the torque M_{K1} is reduced on clutch K1.

Synchronization and Completion Phase According to the earlier presentation, with reduction of engine torque (Fig. 2.4).

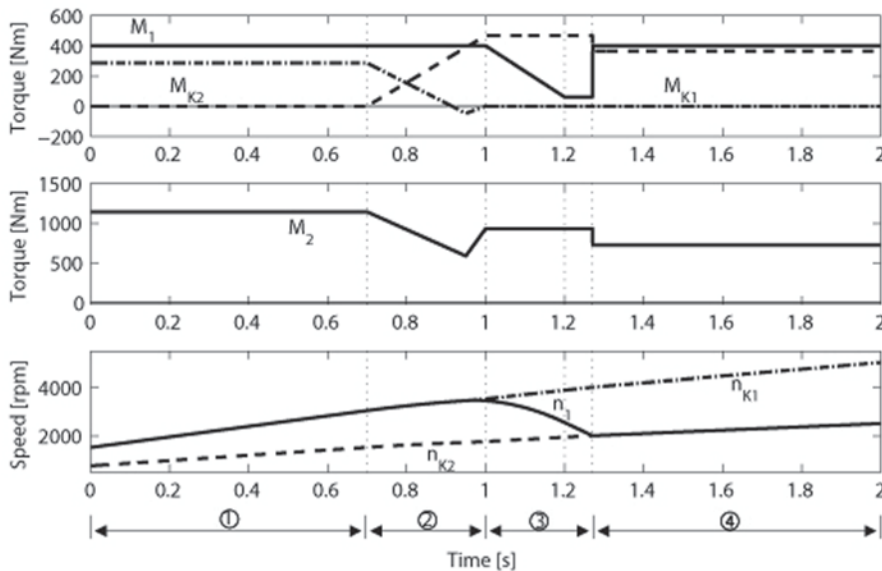


Fig. 2.5 Releasing clutch too slow

Delayed Buildup of Engine Torque after the Synchronization Phase

In the introduction of the clutch in Sect. 1.4.1, the transition from slip to stick that accompanies an abrupt torque change is already shown. In the case of the idealized shift with torque control, engine torque must be built up abruptly and precisely at the point in time when clutch K2 begins to stick. Figure 2.6 presents the reactions to a delayed torque buildup.

Preparatory Phase The engine torque is transferred via clutch K1. Clutch K2 is released.

Hand-over Phase According to the earlier presentation with reduction of engine torque (Fig. 2.4).

Synchronization Phase At the end of the phase speed adjustment occurs and the clutch starts to stick. This means that there is no kinetic energy available that could compensate for the lack of torque due to the continuing torque reduction of the engine, as in the first part of the synchronization phase. The output torque M_2 collapses (see also the principle example in Sect. 1.4.1).

Completion Phase The engine torque is built up with time delay, again with a torque change as consequence.

Premature Release of the Delivering Clutch

Figure 2.7 shows the reactions to a premature release of the transferring clutch K1, which are identical to a delayed engaging of the receiving clutch K2.

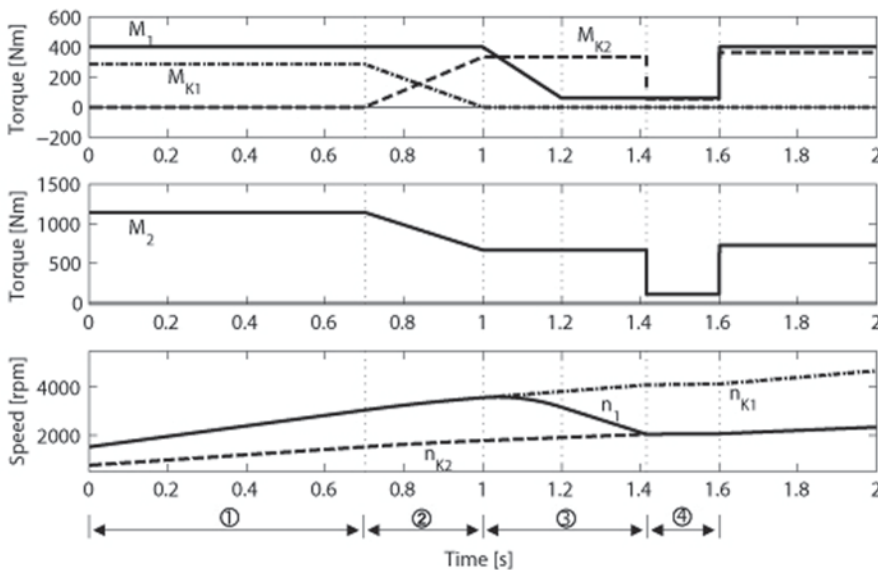


Fig. 2.6 Engine torque buildup delayed

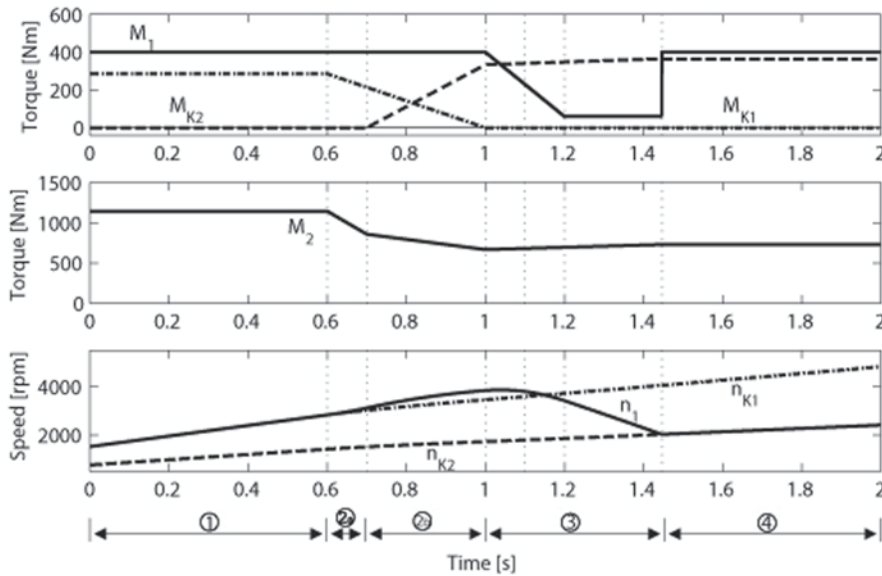


Fig. 2.7 Premature release of the delivering clutch

Preparatory Phase The engine torque is transferred via clutch K1. Clutch K2 is released.

Hand-over Phase In phase 2a the clutch torque on clutch K1, M_{K1} , is already reduced, although clutch K2 has not yet started to engage. Clutch K1 starts to slip. Clutch K2 remains released, $M_{K2} = 0$. The output torque drops with the release of clutch K1, while clutch K2 still remains released. Engine torque M_1 remains constant over the entire hand-over phase. Engine speed n_1 increases beyond the value of the output speed n_{K1} . In phase 2b clutch K2 starts to engage. The output torque M_2 continues to drop accordingly

$$M_2 = i_1 M_{K1} + i_2 M_{K2}. \quad (2.7)$$

However, the drop is less severe than it is in the first part of this phase. Engine speed n_1 continues to increase.

Synchronization Phase Clutch K1 is released ($M_{K1} = 0$). The torque on clutch K2, M_{K2} , is held constant, the engine torque M_1 is reduced through engine control, to enable the synchronization of the speeds, the engine speed n_1 starts to decrease. This causes the output torque M_2 to remain constant in accordance with Eq. (2.5).

Completion Phase In principle, the curves follow the idealized curves shown above (correct timing for buildup of engine torque), only the speed and torque levels are changed due to the deviation in the previous phases.

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