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Experimental Study on Synchronous Shifting for AMT without Synchronizer Based on Three-phase Induction Motor

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Abstract

In order to reduce shifting jerks, synchronous shift is needed on transmission with gear ratios. How to achieve synchronous shift has been the difficulty of AMT (Automated Mechanical Transmission) without synchronizer, which is the main emphasis of shift schedule. In this paper, the experimental study on synchronous up-shifting and down-shifting is given by test-bed which consisted of three-phase induction motor and heavy-duty AMT without synchronizer. Based on shift model, the synchronous speed difference is put forward for the synchronous shift strategy. The synchronizing control strategy of up-shifting is proposed on the basis of the braking characteristics of TB (transmission brake). The synchronizing control strategy of down-shifting is given according to the characteristics of the three-phase induction motor. Under the conditions of various synchronous speed differences, the up-shifting experiments and down-shifting experiments are achieved. By comparisons, the best value of synchronous speed difference is discussed in terms of gear-position and working conditions. The results of shifting experiments show that the synchronous shifting strategies for AMT without synchronizer based on three-phase induction can decrease shifting jerks and improve shift qualities.

Keywords*: three-phase induction motor; automated mechanical transmission; synchronous speed difference; synchronous shift.*

1. Introduction

As is well known, the synchronizer-type transmission has been used for decades in vehicles [1-5]. It still has some difficult technology problems that it cannot be widely used in heavy-duty vehicles. AMT has become a principal selection for heavy truck because it has some advantages in terms of high efficiency and large torque. Therefore, it is of great importance to study synchronous shift for heavy-duty AMT without synchronizer. In this paper, synchronous shift test is studied by test-bed for heavy-duty AMT without synchronizer base on three-phase induction. The test provides an experimental basis for the theory of AMT driving belt conveyors [6-7].

First of all, synchronous speed difference is put forward to be used as the condition for synchronous shift. Secondly, with the help of analyzing the characteristics of TB and three-phase induction, synchronous up-shifting and down-shifting strategies are discussed. Finally, the comparative experiment results under various synchronous speed differences are given which demonstrate the feasibility of synchronous shift strategy of synchronous speed difference.

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2. Test-bed Profile

As is shown in figure 1, the test-bed which is built in line with the power train includes three-phase induction, AMT, inertia plate, loading equipment. The inertia plate simulates load inertia. The loading equipment simulates load resistance torque which uses hydraulic loading system. The control system of AMT mainly contains upper PC, under computer (TCU), solenoid valves, actuators, and sensors. The schematic diagram of measurement and control system is shown in figure 2.

Data and control commands can be communicated between PC and TCU (Transmission Control Unit) by serial communication. TCU controls AMT actuators indirectly by way of controlling solenoid valves. AMT actuators comprise clutch power cylinder, selector cylinder and shift cylinder. There are five sensors which are input shaft speed sensor, output shaft speed sensor, clutch displacement sensor, selector cylinder displacement sensor, and shift cylinder displacement sensor. The working medium of AMT cylinders is compressed air which is supplied by air compressor.

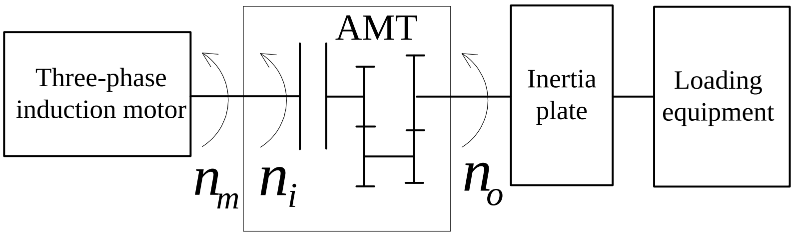


Figure 1. Sketch of Test-bed

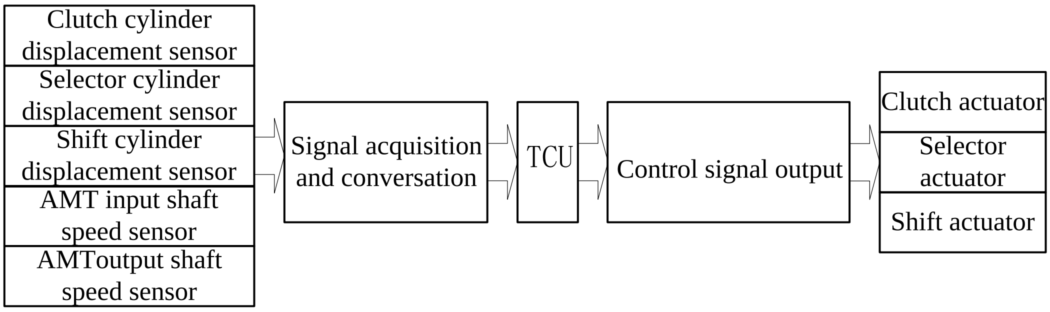


Figure 2. Schematic Diagram of AMT Measurement and Control System

3. Shift Schedule of Synchronous Speed Difference

The whole shift process of AMT without synchronizer can be divided into six stages, including clutch disengaging, taking gears off, selecting gear, synchronizing control, shifting gear, and clutch engaging. Under the influence of load resistance, the output shaft speed slows down quickly during taking gears off, selecting gear, and synchronizing control stages because of power interruption as a result of clutch disengagement. But input shaft speed decreases slowly because of low friction resistance between bearing and input shaft. So, the speed loss of the output shaft speed is larger while that of the input shaft is smaller. In addition, there are thirty milliseconds from computer instruction to actuator's action. The shift model is shown in figure 3. The internal gear ring of the sliding sleeve is connected with the output shaft. With the help of gearshift, the external gear ring of the sliding sleeve is engaged with the internal gear ring of the gear on the output shaft while power can be carried from the input shaft to the output shaft by countershaft. The synchronous shift can be achieved when their speeds are equal.

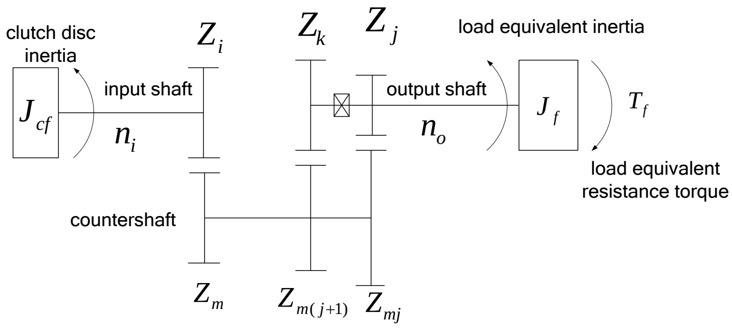


Figure 3. Shift Model

The speed loss of the output shaft during neutral position can be described as:

$$n_{ot2} = n_{ot1} - \Delta n_{oloss} \quad (1)$$

Where n_{ot2} is the output shaft speed at the moment of shifting, n_{ot1} is the output shaft speed at the end of clutch disengaging, Δn_{oloos} is the speed loss of the output shaft during clutch disengagement before shifting.

On the basis of synchronous shift principle, the input shaft speed is required as follows.

$$n_{ik} = n_{ot2} i_k \quad (2)$$

Where n_{ik} is the input shaft speed required at the time of shifting, i_k is the gear ratio of target gear position.

Concerning of the lag time in terms of shift actuator, the input shaft speed and the output shaft speed can not meet the relationship of formula (2) at the moment of shifting. Consequently, synchronous speed difference is regarded as a criterion whether their speeds achieve synchronization or not at the moment of shifting.

The synchronous speed difference is defined as the absolute value of the speed difference between the input shaft speed and that the output shaft speed needs which is the product of the output shaft speed times the target gear's ratio.

$$\Delta n_i = \left| n_{it2} - n_{ot2} i_k \right| \quad (3)$$

Where Δn_i is synchronous speed difference, n_{it2} is the input shaft speed at the moment of shifting instruction offered by TCU.

4. Evaluation Index of Shift Quality

There are some jerks during shift process with gear position's changing. Based on literatures, the objective evaluation indexes of shift comforts are listed as follows.

(1) Evaluation index of dynamic load: the maximum output shaft acceleration $a_{o\max}$

(2) Evaluation index of shifting jerk: the output shaft jerk $j = \dfrac{\pi}{30} \dfrac{d^2{}_{n_o}}{dt^2}$

The maximum jerk of automobile is ten meters per cubic second referenced from Germany [8]. The output shaft jerk can be calculated according to German criteria if the gear ratio of final drive and the tire size are provided. In this paper, the shifting jerk of the transmission output shaft is calculated as 764.15 radians per cubic second.

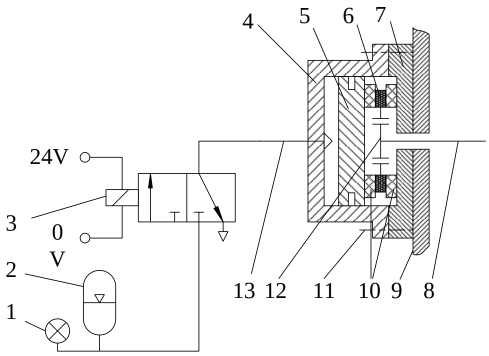
5. Synchronous Shift Control of AMT without Synchronizer

As can be seen from formula (2), the input shaft speed should be increased for up-shift, while it should be decreased for down-shift. The input shaft speed and the output shaft speed can no longer be related after the gear position is in neutral. The input shaft slows down slowly because of low frictions between the input shaft and the counter shaft on account of their constant mesh gears, while the output shaft decreases quickly under the influence of resistance torque.

With the decrease of the output shaft speed, the input shaft speed and the output shaft speed can not meet the condition of synchronous up-shift. In order to achieve synchronous up-shift, the transmission should be interfered to speed down. With the decrease of the output shaft speed, there is always a moment that the input shaft speed and the output shaft speed can meet the condition of synchronous down-shift.

5.1 Braking Characteristics of TB

TB is a brake apparatus for reducing the input shaft speed. The schematic diagram of TB is shown in figure 4. The countershaft will be broken quickly under the action of pneumatic pressure if TB valve is offered power by 24V, and the input shaft speed will be slowed down. But TB brake must be used under the circumstance of neutral position.



1-pressure gage 2-air storage tank 3-TB valve 4-TB bracket 5-piston
6-friction plate 7-end cap 8-countershaft 9-transmission housing
10-TB brake 11-fastening bolt 12-brake gear 13-pneumatic tube

Figure 4. Schematic Diagram of TB

Under neutral position, the changes of the input shaft speed under various values of TB PWM (Pulse Width Modulation) conditions are given in figure 5. It can be seen from figure 5 that the input shaft speed slows down more quickly with bigger value of TB PWM. Therefore, the input shaft speed can be controlled by controlling the value of TB PWM.

The bake torque under various values of TB PWM conditions can be calculated from formula (4).

$$T_{tb} = \frac{\pi}{30} J_{cf} \frac{dn_i}{dt} \tag{4}$$

Where J_{cf} and T_{tb} are clutch disk inertia and brake torque respectively.

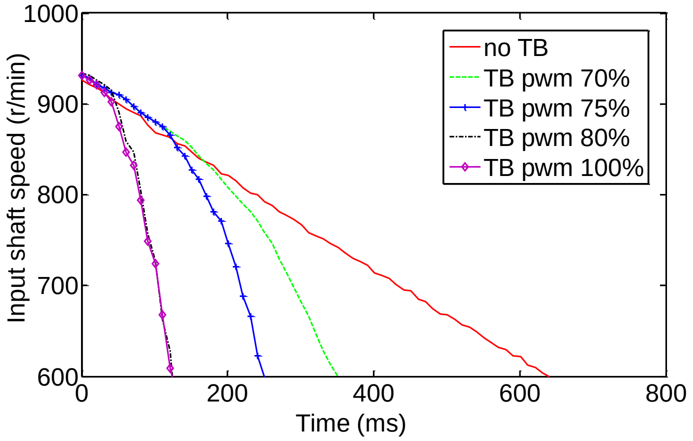


Figure 5. Input Shaft Speed Contrast under the Conditions of Various TB PWM Value

5.2 Synchronous Up-shift Control

The speed loss of transmission output shaft after taking gears off can be expressed as

$$\Delta n_o = \frac{30}{\pi} \frac{T_f \Delta t}{J_f} \tag{5}$$

Where Δn_o and Δt are the speed loss of output shaft and the time from the termination of taking gears off to the beginning of shifting respectively, T_f and J_f are load equivalent resistance torque and load equivalent inertia on the output shaft respectively.

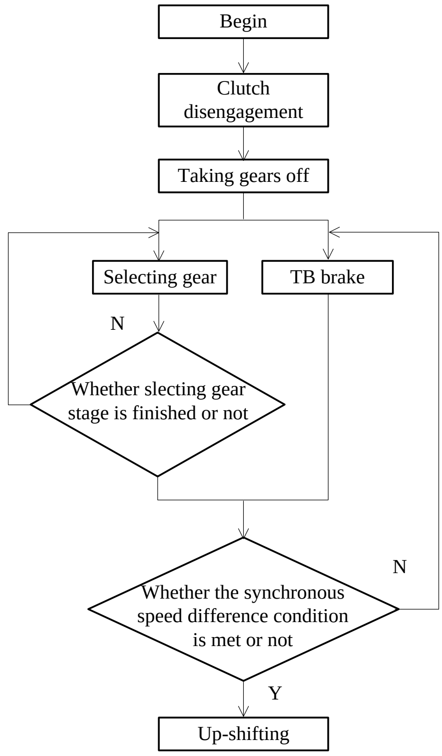


Figure 6. Synchronization Flow for Up-shift

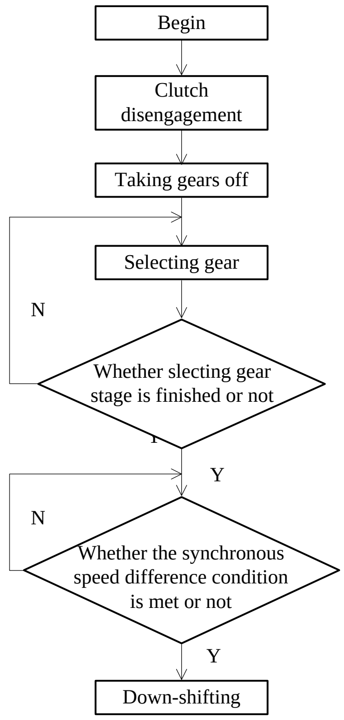


Figure 7. Synchronization Flow for Down-shift

In order to reduce speed loss of the output shaft and shorten synchronization time before shifting, the input shaft can be broken during the time of selecting gear stage. Synchronization flow for up-shifting is shown in figure 6.

The synchronization process is finished and TB valve should be closed if the synchronous speed difference value can meet the up-shifting condition.

$$\Delta n_i = n_{it2} - n_{ot2} i_k \le \Delta n_{iup} \quad (6)$$

Where Δn_{iup} is the threshold value of synchronizing control for up-shift.

The value of TB PWM and the reduction of the input shaft can be compiled as a database on the basis of large amounts of test data. The value of TB PWM and the desired reduction of the input shaft can be determined by seeking table in practical synchronizing control of up-shift for AMT without synchronizer. Under the same load conditions, the higher number of TB PWM and the lower number of synchronous speed difference should be selected with the increase of resistance torque. With the gear position's rising, the higher synchronous speed difference should be chosen in view of lower reduction of the input shaft under the same load and resistance torque circumstances. In addition, the higher value of TB PWM and the lower synchronous speed difference should be selected with the increase of T_f / J_f when it will be up-shifted to the same gear position.

5.3 Synchronous Down-shift Control

The required speed of the input shaft should be increased for down-shift according to formula (2). But the speed of three-phase induction varies little within load ranges. How to achieve synchronization can only be solved from the way of their speed losses. One way is using twice clutch actions that clutch engagement is taken during selecting gear stage to increase the input shaft speed and then the clutch disengagement is used to prepare for down-shift operation which makes it more difficult to control clutch operations. Another way is that the input shaft waits the output shaft because there is always a moment that their speeds meet the synchronization condition. The shortcoming of the second way is that it will prolong the whole time of shift process. The second way is used in the paper for its simple control. The synchronization flow for down-shifting is given in figure 7.

The synchronization condition is finished when the input shaft and the output shaft meet the below expression.

$$\Delta n_i = n_{ot2} i_k - n_{it2} \le \Delta n_{idown} \quad (7)$$

Where Δn_{idown} is the threshold value of synchronizing control for down-shift.

Under the same load circumstances, a higher synchronous speed difference should be selected with the increase of resistance torque. With the gear position's dropping, a higher synchronous speed difference should be chosen on account of more speed loss of the output shaft under the conditions of same load and resistance torque. In addition, a higher synchronous speed difference should be selected with the increase of T_f / J_f when gear position will be down-shifted to the same position.

6. Experiment Results

Test data about synchronization control and no synchronization control for up-shift and down-shift are given by test-bed under the heavily loaded conditions. Sampling time starts from the beginning of clutch disengaging stage and ends up the finishing of shifting action.

6.1 Experiment Results of Up-shifting

6.1.1 Up-shift under the Condition of Synchronous Speed Difference

As is shown in figure 8, 9, 10 and 11, the speeds, accelerations, and jerks of the input shaft and the output shaft are given respectively from third gear to fourth gear under various synchronous speed differences heavily loaded conditions. Figure 12, 13, 14 and 15 are given from fourth gear to fifth gear under various synchronous speed differences heavily loaded conditions.

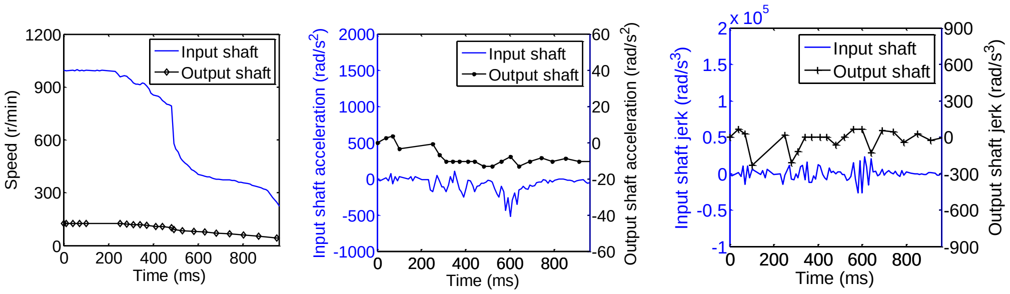


Figure 8. Contrast from Third Gear to Fourth Gear under 60 r/min Synchronous Speed Difference Condition

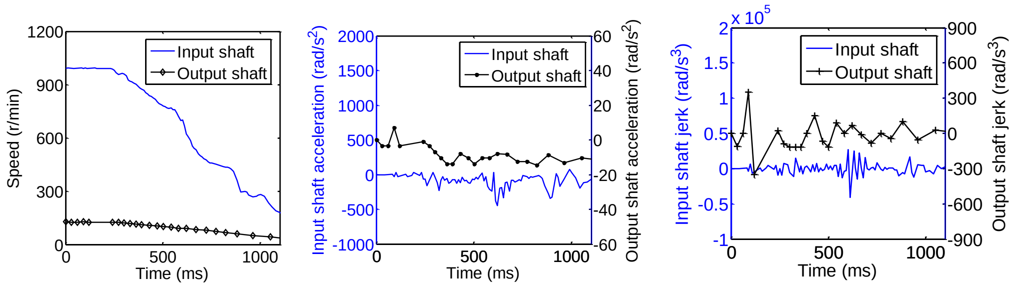


Figure 9. Contrast from Third gear to Fourth Gear under 80 r/min Synchronous Speed Difference Condition

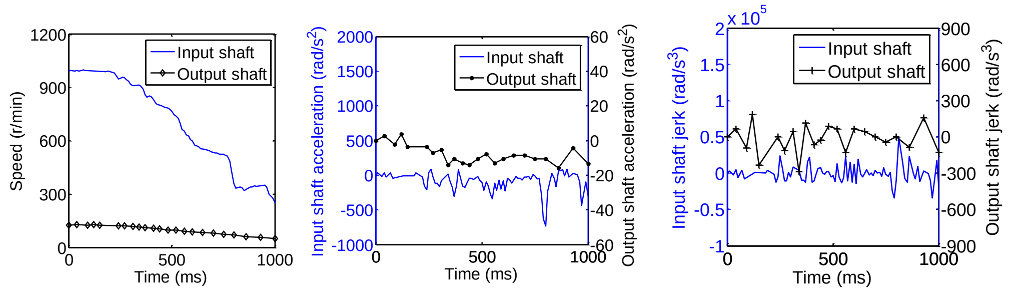


Figure 10. Contrast from Third Gear to Fourth Gear under 100 r/min Synchronous Speed Difference Condition

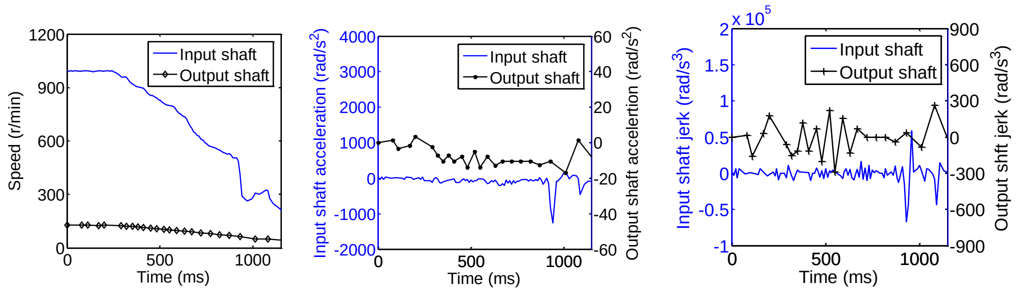


Figure 11. Contrast from third Gear to Fourth Gear under 120 r/min Synchronous Speed Difference Condition

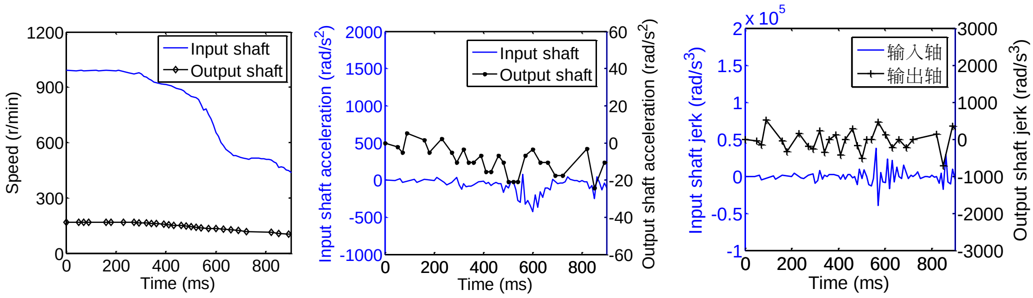


Figure 12. Contrast from Fourth Gear to Fifth Gear under 60 r/min Synchronous Speed Difference Condition

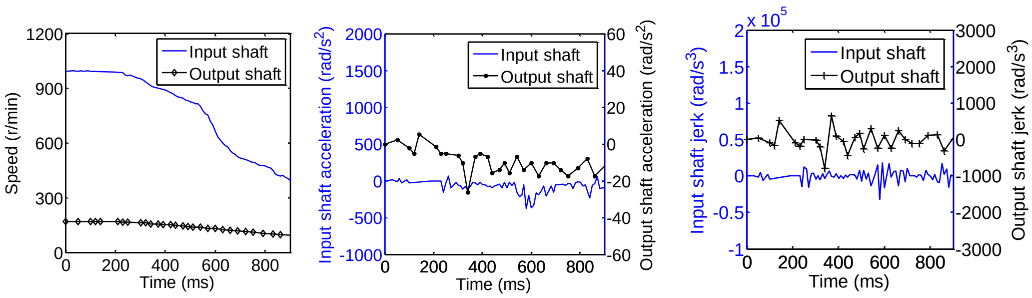


Figure 13. Contrast from Fourth Gear to Fifth Gear under 80 r/min Synchronous Speed Difference Condition

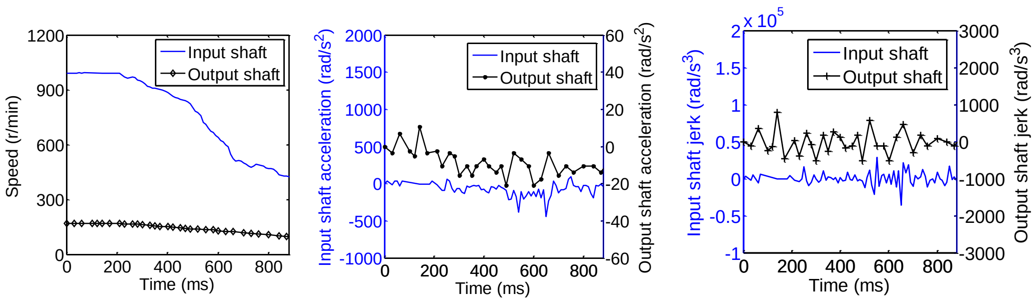


Figure 14. Contrast from Fourth Gear to Fifth Gear under 100 r/min Synchronous Speed Difference Condition

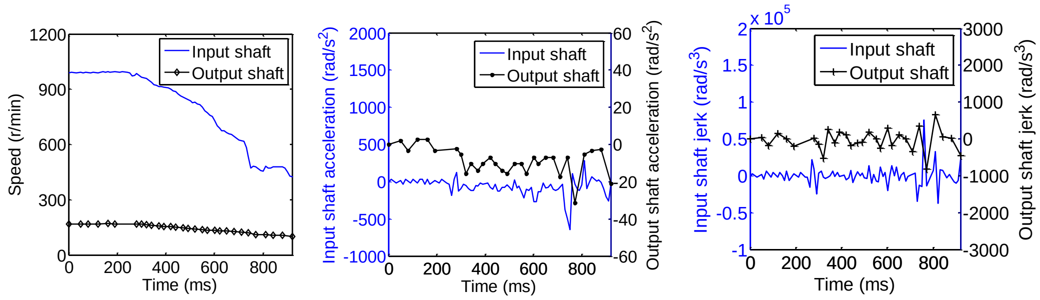


Figure 15. Contrast from Fourth gear to Fifth Gear under 120 r/min Synchronous Speed Difference Condition

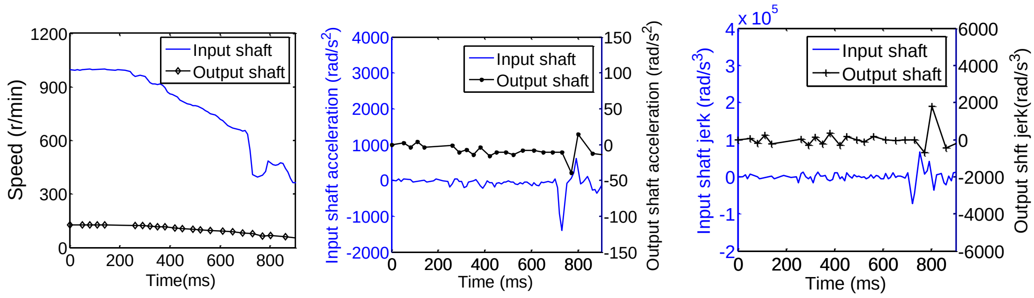


Figure 16. Contrast from Third Gear to Fourth Gear under No Synchronization Control

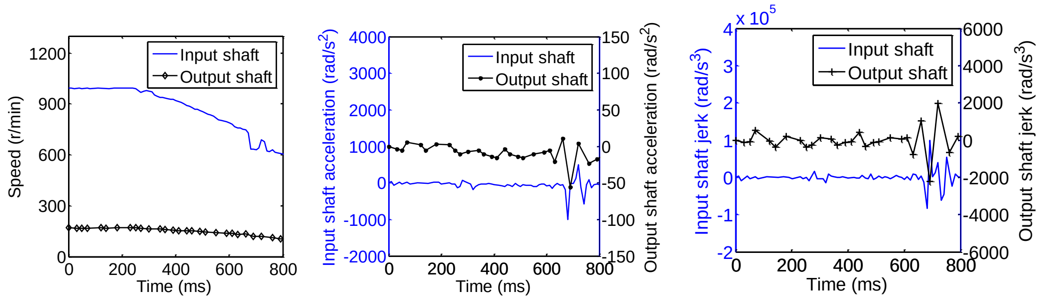


Figure 17. Contrast from Fourth Gear to Fifth Gear Under No Synchronization Control

6.1.2 Up-shift under the condition of no synchronization

As is shown in figure 16 and 17, test results are obtained under no synchronization heavily loaded conditions.

6.1.3 Analysis of up-shift test

As is shown in table 1, the contrasts are listed under various synchronous speed differences heavily loaded conditions. T he value of the input shaft speed is lower at the end of TB brake and the brake time is longer when the lower synchronous speed difference value is chosen. In experimental data of up-shift from third gear to fourth gear, the maximum values of the output shaft acceleration and jerk during shifting stage are -10 radians per square second and 41 radians per cubic second separately under the synchronous speed difference condition of 60 revolutions per minute which are less than that under other synchronous speed difference conditions. The maximum values of the output shaft acceleration and jerk during shifting stage are 17 radians per square second and -319 radians per cubic second respectively under the synchronous speed difference condition of 80 revolutions per minute which are the least in experimental data of up-shift from fourth gear to fifth gear. That is to say, with the gear position's rising, the higher synchronous speed difference should be chosen under the same load and resistance torque circumstances.

Table 1. Up-shift Characteristics under Various Synchronous Speed Differences Heavily Loaded Conditions

Target gear position	Synchronous speed difference (r/min)	Input shaft /output shaft speed at the end of TB (r/min)	Input shaft/output shaft acceleration during shifting stage (rad/s^2)	Input shaft jerk /output shaft jerk during shifting stage (rad/s^3)
4	60	595/92	-355/-10	-9943/41
	80	603/89	-345/-14	17008/98
	100	633/91	-732/-15	49193/160
	120	670/93	-1266/-17	-66987/264
5	60	633/134	-293/-27	-34540/-814
	80	649/134	-230/-17	16747/-319
	100	691/136	-439/-20	-35587/465
	120	701/136	-648/-31	75360/-814

As can be seen from figure 16 and 17, the values of the output shaft acceleration and jerk under no synchronization control during shifting stage are obviously larger than that under synchronous speed difference conditions. The maximum values of the output shaft acceleration and jerk are -39 radians per square second and 1773 radians per cubic second during shifting stage from third gear to fourth gear. The maximum values of the output shaft acceleration and jerk are -55 radians per square second and -2209 radians per cubic second during shifting stage from fourth gear to fifth gear. By contrast, shift jerk can be controlled within some limits if the synchronous shift strategy of up-shift is adopted.

The value of synchronous speed difference has an influence on up-shift which can be illustrated from figure 12, 13 and 15. The input shaft speed rises quickly at the moment of shifting and it drops quickly after the shifting is completed in figure 12 which shows the input shaft speed is lower than that the output shaft needs because of excessive braking. The input shaft speed drops quickly at the moment of shifting and it rises quickly after the shifting is finished in figure 15 which explains the input shaft speed is higher than that the output shaft needs on account of deficient braking. The input shaft speed changes gently and the values of the output shaft acceleration and jerk are low during shifting stage in figure 13 which illustrates the input shaft and the output shaft achieve their synchronous speeds at the moment of shifting resulting in lower shifting jerk.

6.2 Experiment Results of Down-shifting

6.2.1 Down-shift under the Condition of Synchronous Speed Difference

As is shown in figure 18, 19, 20 and 21, the speeds, accelerations, and jerks of the input shaft and the output shaft are provided successively from fourth gear to third gear under various synchronous speed difference heavily loaded conditions. Figure 22, 23, 24 and 25 are given from fifth gear to fourth gear under various synchronous speed differences heavily loaded conditions.

6.2.2 Down-shift under the Condition of No Synchronization

As can be seen in figure 26 and 27, test results are obtained under no synchronization heavily loaded conditions.

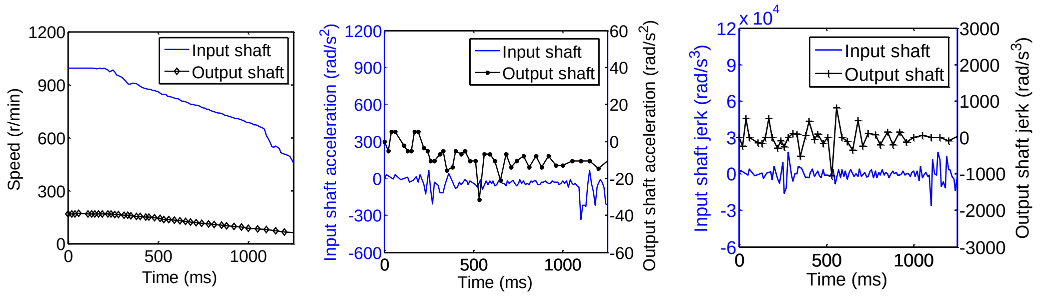


Figure18. Contrast from Fourth Gear to Third Gear under 60 r/min Synchronous Speed Difference Condition

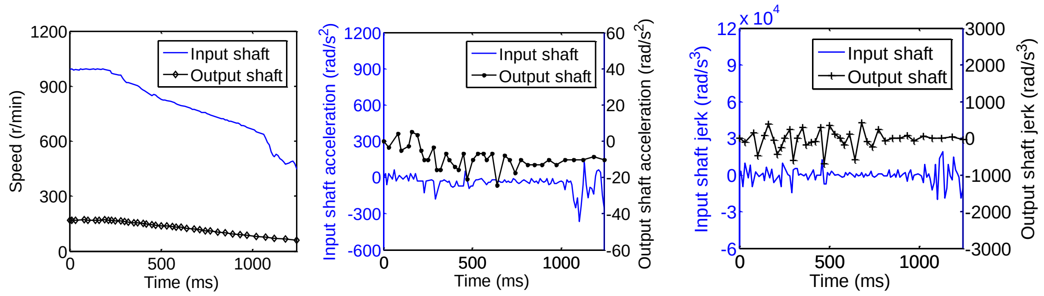


Figure 19. Contrast from Fourth Gear to Third Gear under 80 r/min Synchronous Speed Difference Condition

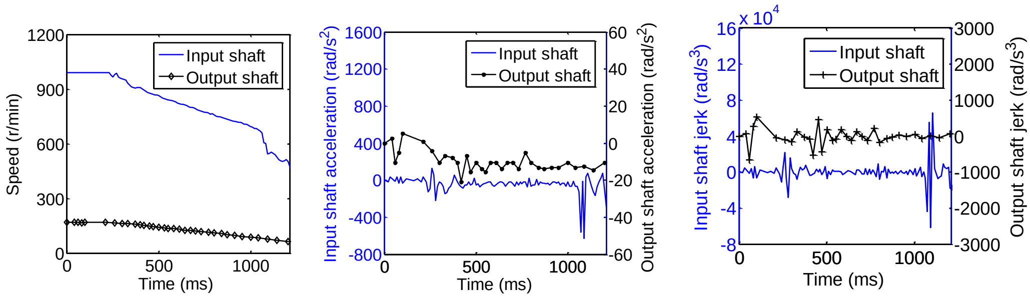


Figure 20. Contrast from Fourth Gear to Third Gear under 100 r/min Synchronous Speed Difference Condition

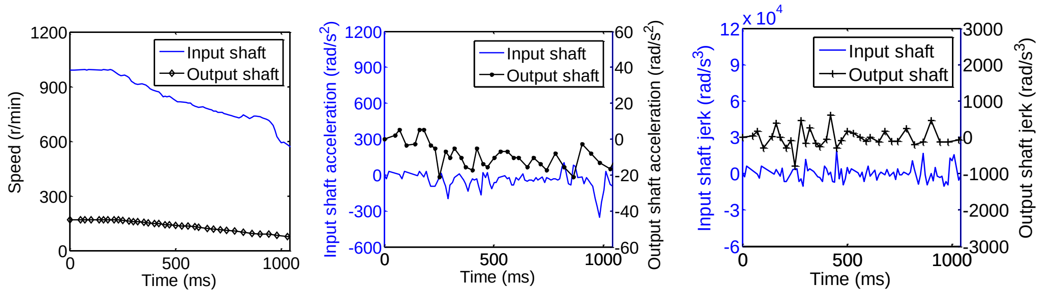


Figure 21. Contrast from Fourth Gear to Third Gear under 120 r/min Synchronous Speed Difference Condition

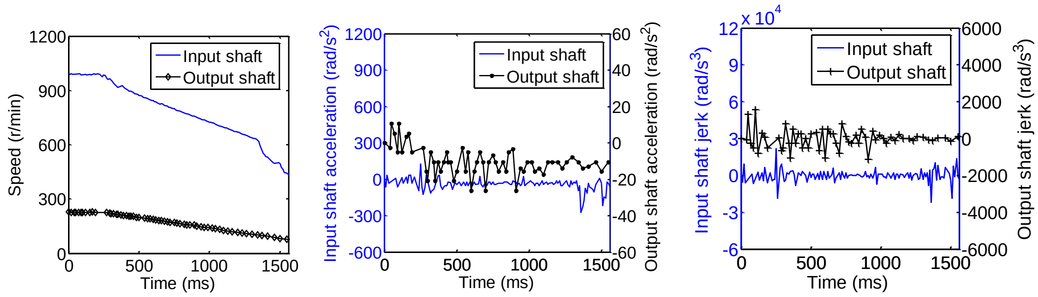


Figure 22. Contrast from Fifth Gear to Fourth Gear under 60 r/min Synchronous Speed Difference Condition

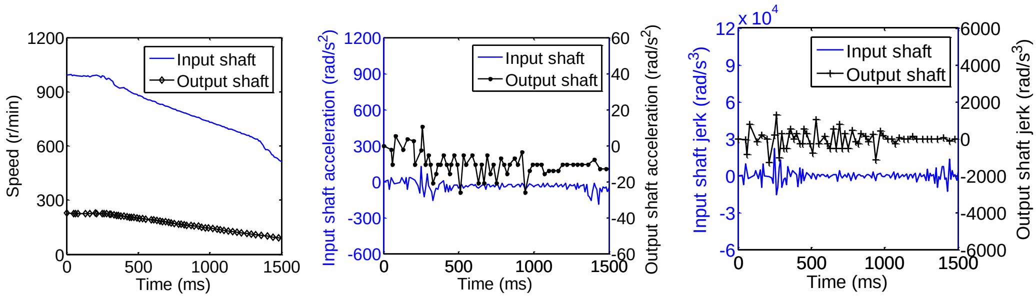


Figure 23. Contrast from Fifth Gear to Fourth Gear under 80 r/min Synchronous Speed Difference Condition

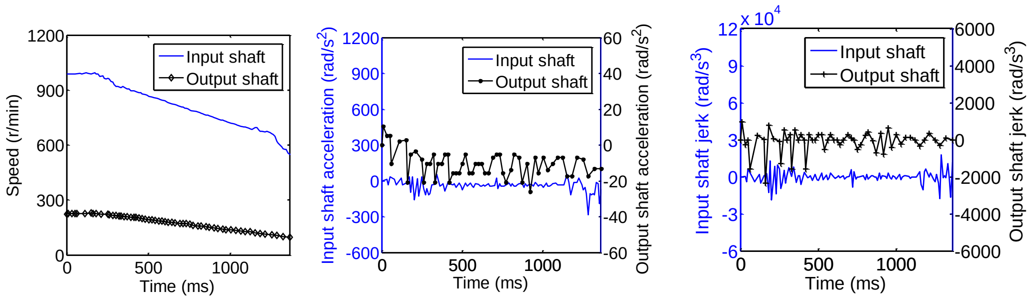


Figure 24. Contrast from Fifth Gear to Fourth Gear under 100 r/min Synchronous Speed Difference Condition

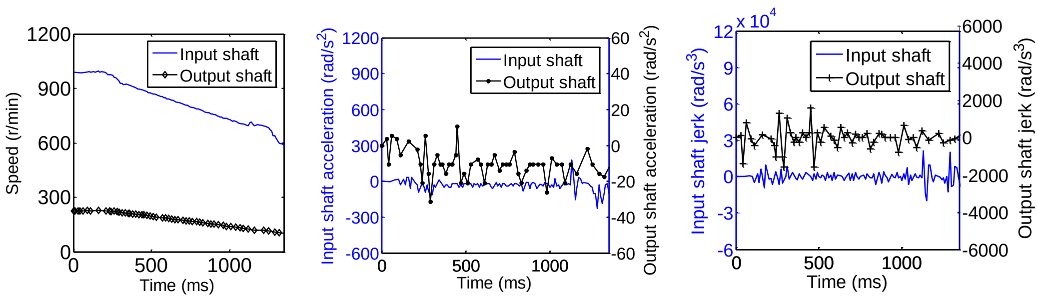


Figure 25. Contrast from Fifth Gear to Fourth Gear under 120 r/min Synchronous Speed Difference Condition

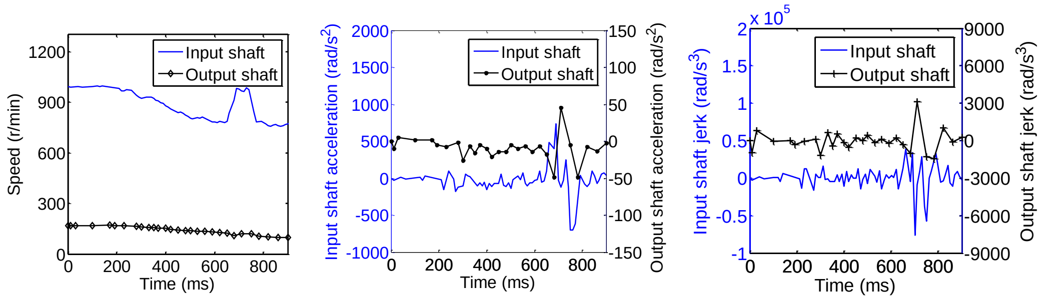


Figure 26. Contrast from Fourth Gear to Third Gear under No Synchronization Control

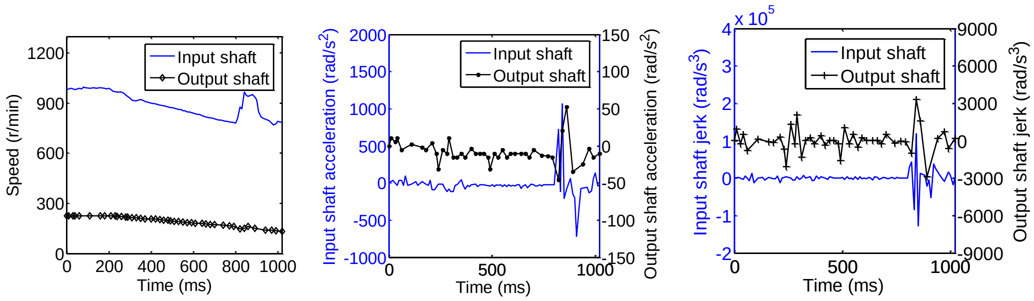


Figure 27. Contrast from Fifth Gear to Fourth Gear under No Synchronization Control

6.2.3 Analysis of Down-shift Test

As can be seen from the test results for down-shift, the values of the output shaft acceleration and jerk under no synchronization control during shifting stage are obviously much more than that under synchronous speed difference conditions. The values of the output shaft acceleration and jerk are -48.8444 radians per square second and 3140 radians per cubic second during shifting stage from fourth gear to third gear under no synchronization control. The values of transmission output shaft acceleration and jerk are 52 radians per square second and 3314 radians per cubic second separately during shifting stage from fifth gear to fourth gear under no synchronization control.

As is shown in table 2, the contrasts are listed under various synchronous speed differences heavily loaded conditions. In experimental data of down-shift from fourth gear to third gear, the maximum values of the output shaft acceleration and jerk during shifting stage are -13 radians per square second and 65 radians per cubic second respectively under the synchronous speed difference condition of 80 revolutions per minute which is less than that under other synchronous speed differences conditions. In experimental data of down-shift from fifth gear to fourth gear, the maximum values of the output shaft acceleration and jerk during shifting stage are -13 radians per square second and -130 radians per cubic second separately under the synchronous speed difference condition of 80 revolutions per minute which is less than that under other synchronous speed differences conditions. As compared to down-shift without synchronization control, the synchronous shift control of down-shift provides lower shift jerk.

Table 2. Down-shift Characteristics under Various Synchronous Speed Differences Heavily Loaded Conditions

Target gear position	Synchronous speed difference (r/min)	Input shaft /output shaft speed at the final of TB (r/min)	Input shaft/output shaft acceleration during shifting stage (rad/s^2)	Input shaft jerk /output shaft jerk during shifting stage (rad/s^3)
3	60	712/96	-334/-14	-26167/-130
	80	719/99	-366/-13	-19887/65
	100	745/106	-565/-14	65940/69
	120	749/110	-355/-20	16747/457
4	60	697/126	-272/-15	-21980/232
	80	706/132	-188/-13	13607/-130
	100	746/144	-230/-26	16747/-697
	120	749/148	-261/-27	20933/-785

The influences of synchronous speed difference value on down-shift effects can be elaborated from figure 22, 23 and 25. The shifting jerk is the least during shifting stage in figure 23 under 80 r/min synchronous speed difference because the input shaft is approximately equal to the synchronous speed the output shaft needs at the moment of shifting. The shifting jerk in figure 22 under 60 r/min synchronous speed difference is bigger than that under 80 r/min synchronous speed difference because the input shaft speed is higher than the synchronous speed the output shaft speed needs. Similarly, the shifting jerk in figure 25 under 120 r/min synchronous speed difference is bigger because the input shaft speed is less than the synchronous speed the output shaft speed needs.

7. Conclusion

All as in conclusion, heavy-duty AMT without synchronizer driven by three-phase induction motor can be achieved synchronous shift by the use of shift schedule of synchronous speed difference in the paper. Based on analyzing the speed losses of the input shaft and the output shaft, the synchronous shift strategy of AMT without synchronizer is discussed. Synchronous speed difference is regarded as the condition of whether the input shaft and the output shaft achieve synchronization or not. Bed-test results prove that the synchronous shift strategy of synchronous speed difference is effective to heavy-duty AMT without synchronizer. In addition, experimental data show that it can improve shift qualities which provide a reference to study the following control law of clutch engagement.

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