

Research Article

Study on Load Parameters Estimation during AMT Startup

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The identification problem of the load parameters is the basis of researching the clutch control strategy and the shift schedule for heavy-duty AMT (Automated Mechanical Transmission). AMT is proposed as the soft starter for the belt conveyor which expands AMT application areas. In order to accomplish the goal of AMT as the soft starter, the load parameters estimation methods including the load resistance torque and the load inertia are firstly studied to accommodate the actual control for AMT startup as the soft starter for belt conveyor. In the paper, the estimation models of the load resistance torque and the load inertia are established during AMT startup for belt conveyor. On the basis of the recursion least squares method, the on-line estimations for the load parameters are recognized according to the test data during AMT startup. The estimation results of these two parameters prove that the load parameters estimation models and the estimation methods during AMT startup are valid.

1. Introduction

Heavy-duty AMT is a type of transmission with complicated working condition and wider load range. The load parameters identification has significant influences on control method and control law for AMT. The researchers have studied the transmitting torque estimation of the clutch during the shifting process in terms of smaller vehicles for decades. Zhao et al. studied the transmitting torque estimation of the clutch during the shifting process on dry double-clutch transmission [1–3]. Pettersson et al. studied the output torque of the vehicle drive shaft during the shifting process based on the transmission model with elastic drive shaft [4, 5]. Baumann et al. designed a Luenberger observer to estimate the actual output torque of the drive shaft [6]. Yi et al. designed a self-adapt slid mode observer to estimate the transmitting torque of the automatic transmission [7]. The identification accuracies of these studies should be verified on real vehicles to demonstrate the theoretical validity. The recursive least squares method is widely used to identify the load parameters. The researchers have studied the least squares parameter estimation methods to for nonlinear system. Wang et al. studied highly efficient identification methods for dual-rate Hammerstein systems [8]. Zhang et al. studied separate block-based parameter estimation method for Hammerstein systems [9].

Belt faults such as breakage and slipping are often caused on account of excessive belt acceleration during the starting process of belt conveyors [10, 11]. Generally, the belt acceleration value is under 0.3 meter per square seconds in order to accelerate the belt conveyor slowly [12–15]. Li et al. studied the starting process and the shifting process for AMT softly starting the belt conveyor based on known load parameters [16, 17]. In application of AMT as the soft starter for belt conveyors, the unknown load parameters should be identified so that the starting process and the shifting process can be better controlled.

The half engagement point of the clutch is a critical point during the starting process which is related to the driving resistance torque on the transmission input shaft. As is known, the half engagement point of the clutch is related to the load resistance torque and the gear position. As a result, it is different if the load resistance torque or the gear position is different. In consequence, the identification for the half engagement of the clutch is the premise to recognize the load parameters. In this paper, the characteristics of the half engagement of the clutch will be used to establish the estimation model of the load resistance torque. Then the estimation model of the load inertia is proposed on the basis of the information about the output shaft speed and the clutch location. The recursion least squares method is applied to the load inertia estimation during AMT startup.

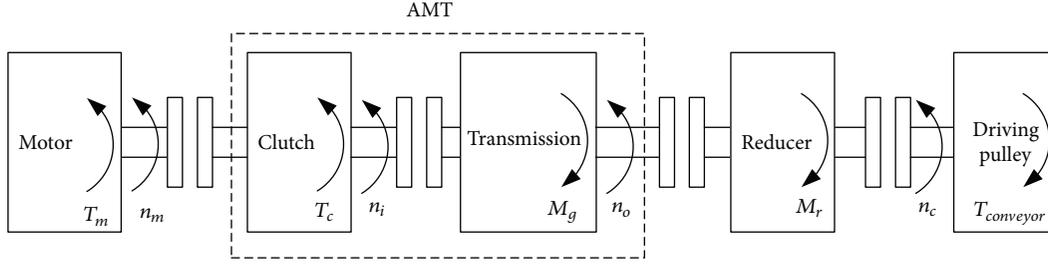
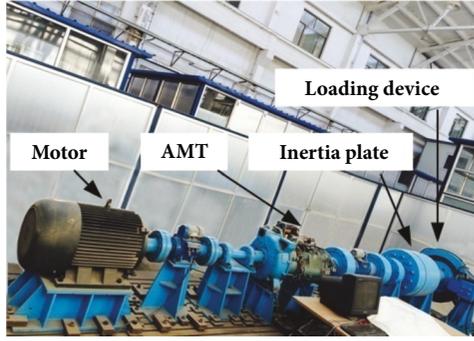
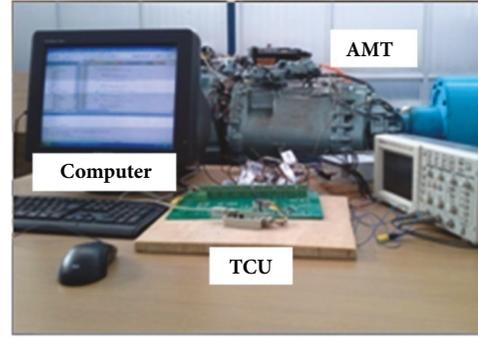


FIGURE 1: Drive line of AMT softly starting the belt conveyor.



(a) AMT test bed composition



(b) AMT measurement and control system

FIGURE 2: AMT test bed system.

As is shown in Figure 1, the drive line of AMT softly starting the belt conveyor mainly composes of the three-phase induction motor, AMT, the reducer, and the driving pulley of the belt conveyor.

The symbolic meanings are as follows: T_m is the output torque of the three-phase induction motor, T_c is the transmitting torque of the clutch, $T_{conveyor}$ is the resistance torque at the driving pulley of the belt conveyor, M_g is the friction loss of the transmission, M_r is the friction loss of the reducer, n_m is the motor speed, n_i is the input speed of the transmission, n_o and n_c are the output speed of the transmission and the driving pulley speed separately.

2. Structure of AMT Test Bed

AMT test bed consisting of the three-phase induction motor with 55 kilowatts, the efficiency instrument, HW19710 type pneumatic AMT manufactured by China Sinotruck, the inertia plate which is used to simulate the load inertia, the loading device which is used to simulate the load resistance torque, the hydraulic station which is used to provide the hydraulic pressure for the loading device to change the resistance torque conveniently, the air compressor which is used to provide the compressed air for AMT actuator, the AMT measurement and control system which is used to provide the command controls, and the sensors signal collections for communicates between AMT and the computer. The reduce gearbox is omitted for the limited space in the laboratory. The test bed system is shown in Figure 2.

3. Identification Models of the Load Parameters

3.1. Clutch Torque Characteristics. As is known, the torque characteristics of the dry clutch are related to the wear loss. Based on the clutch displacement sensor and the input shaft speed sensor, the estimation of the clutch wear loss can be measured which the diagram of the wear testing program is shown in Figure 3.

The dry clutch torque characteristics can be expressed by the displacement of the clutch actuator with a cubic displacement polynomial in

$$T_c(x_c) = \mu' \left[K_1(x_c - x_{ce} - \Delta x_{ce}) + K_2(x_c - x_{ce} - \Delta x_{ce})^2 + K_3(x_c - x_{ce} - \Delta x_{ce})^3 \right] \quad (1)$$

where K_1 , K_2 , and K_3 are first-order coefficient, second-order coefficient, and third-order coefficient respectively, μ' is the dynamic friction coefficient between the driving disc and the fiction disc, x_c is the displacement of the clutch actuator, x_{ce} is the corresponding displacement of the clutch actuator related to the critical point of the new clutch empty running, and Δx_{ce} is the increase of the clutch actuator empty running displacement caused by the clutch wear.

3.2. Estimation Model of the Load Resistance Torque. The load resistance torque can be estimated on the basis of the relationship between the half engagement joint and the clutch

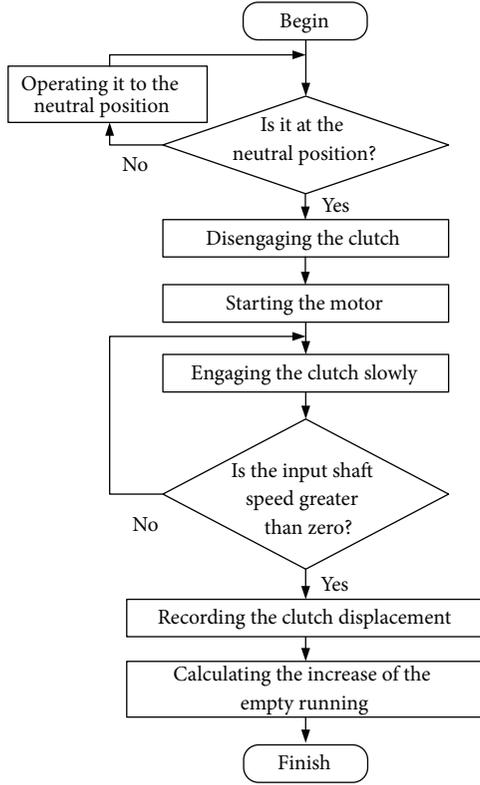


FIGURE 3: The diagram of the clutch wear testing program.

transmitted torque. The signal of the transmission output shaft speed sensor can be collected after the signal gear turns the first tooth. The speed of the transmission output shaft can be measured as long as the output shaft turns. The load resistance torque can be calculated until the transmission control unit collects the first output shaft speed signal during the starting process.

The estimation model for the equivalent load resistance torque on the transmission output shaft can be expressed in

$$\hat{T}_{load} = T_c(x_{hc}) \eta_g i_g \quad (2)$$

where \hat{T}_{load} is the load equivalent resistance torque, $T_c(x_{hc})$ is the clutch transmitted torque at the half engagement point, x_{hc} is the actuator corresponding position for the clutch engagement joint, and η_g and i_g are the transmission efficiency and ratio separately.

3.3. Estimation Model for the Load Inertia. We suppose that the load resistance torque is invariable during the starting process. The load inertia can be estimated by the use of the momentum theorem on the basis of the clutch transmitted torque and the output shaft speed. The time when the transmission output speed is more than zero is considered as the zero time for the load inertia estimation. Δt_s is the interval time which is ten millisecond in this paper. The sampling times are zero, t_1 , t_2 , ..., and t_n orderly. The clutch actuator corresponding positions are x_{c0} , x_{c1} , x_{c2} , ..., and x_{cn} orderly. The clutch transmitted torques are T_{c0} , T_{c1} , T_{c2} , ..., and T_{cn}

successively. The transmission output shaft speeds are n_{o0} , n_{o1} , n_{o2} , ..., and n_{on} in sequence.

We suppose that the data updates n times from the beginning of the half engagement joint to the finishing acceleration of the output shaft which it reaches the top speed under the selected gear position. The time of the output shaft speed data updates $m-1$ times (m is less than or equal to n) is defined as t_k and the time of the output shaft speed data update m times is considered as t_l . The parameter of Δn_m is ordered as n_{ol} minus n_{ok} . The load angular momentum on the transmission output shaft can be calculated in (3) during the period of the time of t_k to that of t_l .

$$M_{loadm} = \left[\left(\frac{T_{ck} + T_{cl}}{2} + \sum_{x=k+1}^{l-1} T_{cx} \right) \eta_g i_g - \hat{T}_{load} (l-k) \right] \Delta t_s \times 10^{-3} \quad (3)$$

Consequently, the observation equation between the load angular momentum on the transmission output shaft and the unknown load inertia during the period of the time of t_k to that of t_l can be expressed in

$$M_{loadm} = \frac{\pi \Delta n_m}{30} J_{load} + v_m \quad (4)$$

where J_{load} is the load equivalent inertia on the transmission output shaft.

The observation matrix of the load equivalent inertia on the transmission output shaft can be described in (5) if the load angular momentum on the transmission output shaft can be taken as the observation matrix and the output shaft speed variation can be treated as the gain matrix.

$$M_{loadi} = H_i J_{load} + V_i \quad (5)$$

where i is equal to 1, 2, ..., m , M_{loadi} is the observation matrix which is equal to the transpose of $[M_{load1} \ M_{load2} \ \dots \ M_{loadm}]$, H_i is the gain matrix which is equal to the transpose of $[\Delta n_1 \ \Delta n_2 \ \dots \ \Delta n_m]$, and V_i is the measurement error matrix which is equal to the transpose of $[v_1 \ v_2 \ \dots \ v_m]$.

3.4. Recursion Least Squares Estimation Method of the Load Inertia. \hat{J}_{load} is the estimation value of J_{load} which is the load inertia. The quadratic index of the least squares estimation for the load inertia can be shown in

$$J_w(\hat{J}_{load}) = (M_{loadm} - H_m \hat{J}_{load})^T W_m (M_{loadm} - H_m \hat{J}_{load}) \quad (6)$$

where $(M_{loadm} - H_m \hat{J}_{load})^T$ is the transposed matrix of $(M_{loadm} - H_m \hat{J}_{load})$ and W_m is a positive weighting matrix.

If the mean value of the observation errors is zero and the variance matrix is Q_m which is equal to the mathematical expectation of the product between V_m and its transpose, the optimal weighting least squares estimation for the load inertia

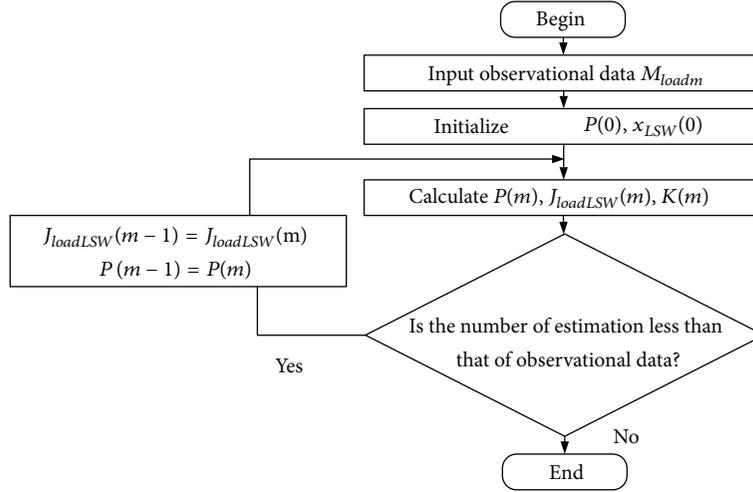


FIGURE 4: The flow block diagram of the recursive least squares estimation algorithm.

with m sets of observation data can be expressed in (7) under the condition that the weighting matrix of W_m is equal to the inverse of the variance matrix of Q_m .

$$\hat{J}_{loadLSW}(m) = [H_m^T Q_m^{-1} H_m]^{-1} H_m^T Q_m^{-1} M_{loadm} \quad (7)$$

where Q_m^{-1} is the inverse matrix of Q_m , H_m^T is the transpose matrix of H_m , and $[H_m^T Q_m^{-1} H_m]^{-1}$ is the inverse matrix of $[H_m^T Q_m^{-1} H_m]$.

In the same way, the optimal weighting least squares estimation for the load inertia with one plus m sets of observation data can be expressed in

$$\begin{aligned} \hat{J}_{loadLSW}(m+1) \\ = [H_{m+1}^T Q_{m+1}^{-1} H_{m+1}]^{-1} H_{m+1}^T Q_{m+1}^{-1} M_{load(m+1)} \end{aligned} \quad (8)$$

where Q_{m+1} is equal to $\begin{bmatrix} Q_m & 0 \\ 0 & q_{m+1} \end{bmatrix}$ and q_{m+1} is the measurement error variance of number $m+1$ times.

If P_m and P_{m+1} are $H_m^T Q_m^{-1} H_m$ and $H_{m+1}^T Q_{m+1}^{-1} H_{m+1}$ separately, the recursive least squares estimation for the load inertia can be expressed in (9) when the number $m+1$ set of test data is observed.

$$\begin{aligned} \hat{J}_{loadLSW}(m+1) &= \hat{J}_{loadLSW}(m) \\ &+ K_{m+1} [M_{load(m+1)} - h_{m+1} \hat{J}_{LSW}(m)] \\ K_{m+1} &= P_{m+1}^{-1} h_{m+1}^T q_{m+1}^{-1} \\ P_{m+1}^{-1} &= P_m^{-1} \\ &- P_m^{-1} h_{m+1}^T (q_{m+1} + h_{m+1} P_m^{-1} h_{m+1}^T)^{-1} h_{m+1} P_m^{-1} \end{aligned} \quad (9)$$

The recursive least squares estimation for the load inertia is finished until the number of estimation is equal to that of observational data. The recursive least squares estimation algorithm for the load inertia can be shown in Figure 4.

4. Real-Time Estimation of the Load Parameters Based on the Recursive Least-Square Algorithm

4.1. Estimation of the Load Parameters. The torque-displacement characteristics of the new clutch can be received which the input torque of the clutch and the output torque of the transmission can be tested using the mechanical efficiency instrument. The experiment methods are described as follows. Firstly, the critical point of the clutch empty stroke is tested on the condition of no load. Secondly, the different half engagement point and the transmitting torque of the clutch can be tested and recorded under the first gear position with the help of the mechanical efficiency instrument and the loading device of which the different resistance torque can be simulated by changing the hydraulic pressure of the hydraulic station. Then, the clutch torque-displacement characteristics in (1) can be expressed with the test data using the method of least squares fit.

On the basis of above methods, the new clutch torque-displacement characteristics in this paper can be expressed approximately in (10) if the friction coefficient μ' is 0.25.

$$\begin{aligned} T_c(x_c) &= 17.2431(x_c - x_{ce}) + 21.0131(x_c - x_{ce})^2 \\ &+ 0.2839(x_c - x_{ce})^3 \end{aligned} \quad (10)$$

The starting process under the first gear is shown in Figure 5 on the condition of unknown load inertia and unknown load resistance torque. Based on (2) and (10), the clutch transmitting torque is 100 N·m. The mechanical efficiency under the first gear is 90 percent by using the efficiency instrument. For this reason, the load resistance torque is 1285.20 N·m.

The zero time of the parameter estimation is determined when the half engagement point is tested. The eighteen sets of observation data with the clutch transmitting torque and the output shaft speed are used to estimate the load inertia. The Gaussian random white noise $N(0,1)$ is added on the basis of

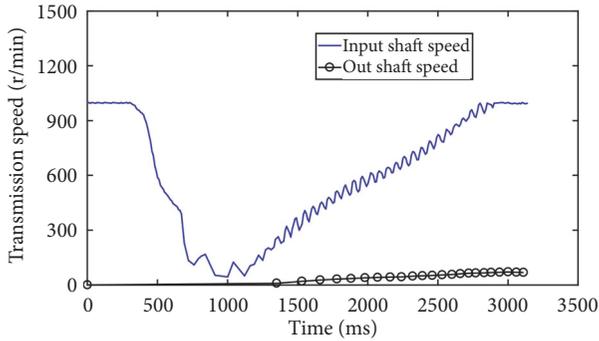


FIGURE 5: The transmission speeds during AMT startup under the first gear.

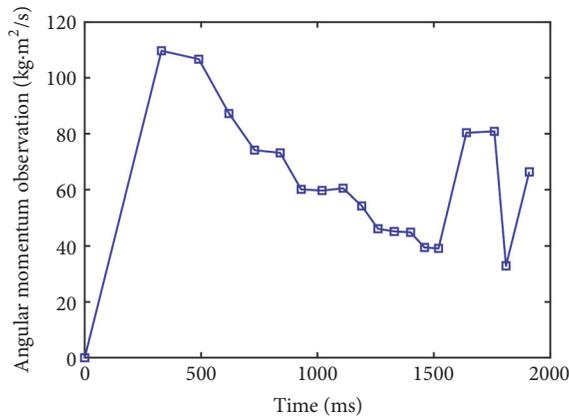


FIGURE 6: Load momentum observation during AMT startup under the first gear.

the observation data. The recursive least squares method is applied in (5) of which the initial value of the load equivalent recursive least squares estimation (RLSE) derived from the top four sets of test data is $261.88 \text{ kg}\cdot\text{m}^2$. The estimation accuracy is defined as the former estimation divided by the difference value of the current estimation value and the former estimation value. The estimation results containing the load momentum observation on the transmission output shaft, the load equivalent inertia estimation (the recursive least squares estimation of the load equivalent inertia on the transmission output shaft), and the estimation accuracy are shown in Figures 6, 7, and 8 respectively.

On the same working condition above, the starting process under the third gear is shown in Figure 9. Forty-one sets of observation data with the clutch transmitting torque and the output shaft speed during the starting process under the third gear are used to estimate the load inertia using the recursive least squares method. The zero time of the parameter estimation is still determined when the half engagement point is tested. The Gaussian random white noise $N(0,1)$ is added on the basis of the observation data. The recursive least squares method is applied in (5) of which the starting value of RLSE derived from the top four sets of test data is $69.76 \text{ kg}\cdot\text{m}^2$. The estimation results of the load momentum observation, the recursive least squares

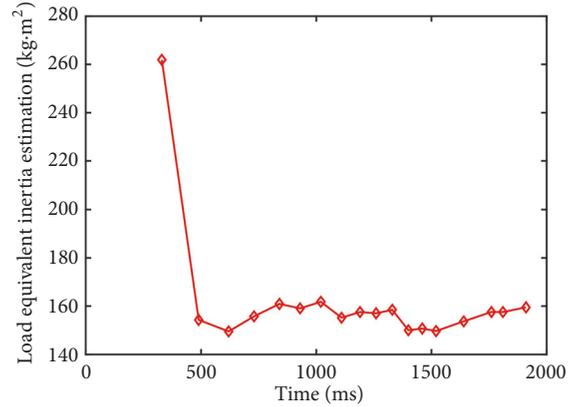


FIGURE 7: RLSE of the load equivalent inertia during AMT startup under the first gear.

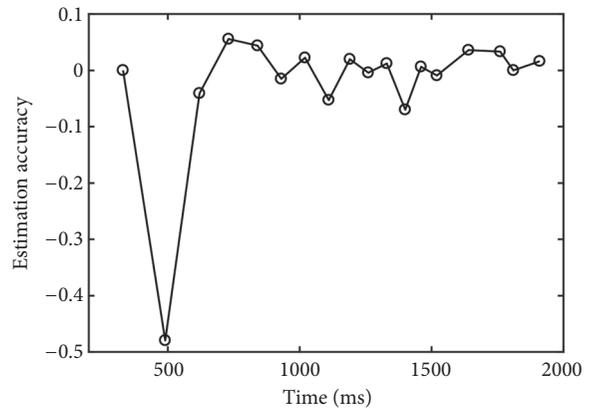


FIGURE 8: Estimation accuracy during AMT startup under the first gear.

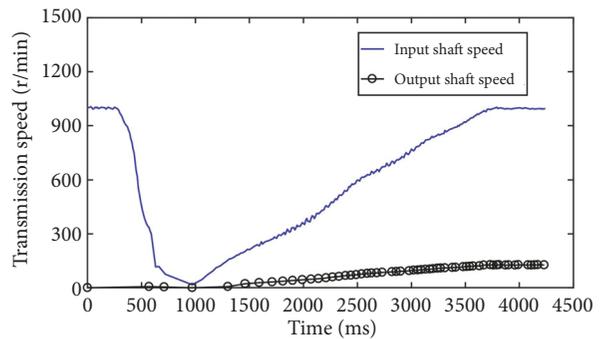


FIGURE 9: The transmission speeds during the starting process under the third gear.

estimation of the load equivalent inertia on the transmission output shaft, and the estimation accuracy are betrayed in Figures 10, 11, and 12 separately.

4.2. Analyzation of Estimation Results. The value of the actual test bed inertia plate is $130 \text{ kg}\cdot\text{m}^2$. As a result, the actual load equivalent inertia on the transmission output shaft under the

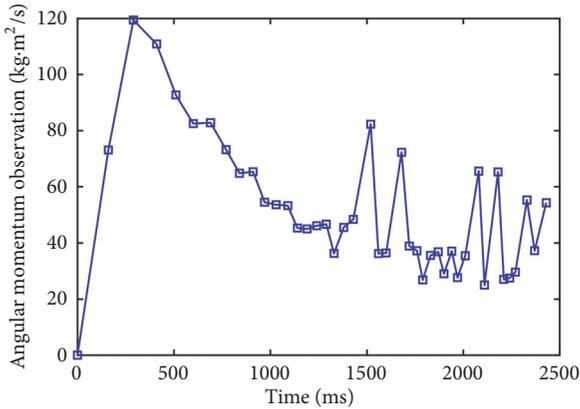


FIGURE 10: Load momentum observation during AMT startup under the third gear.

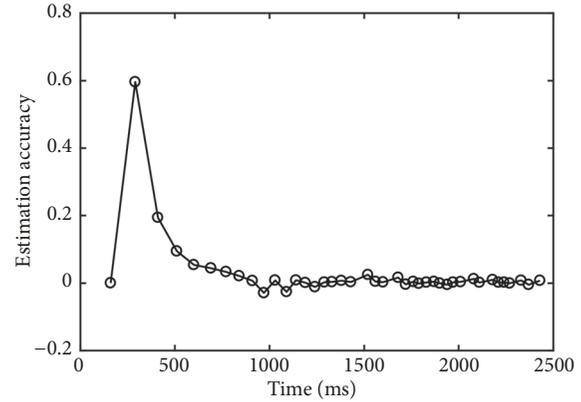


FIGURE 12: Estimation accuracy during AMT startup under the third gear.

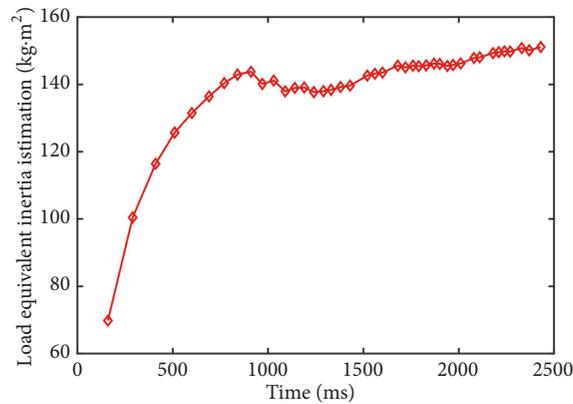


FIGURE 11: RLSE of the load equivalent inertia during AMT startup under the third gear.

first gear is $167.53 \text{ kg}\cdot\text{m}^2$ and that under the third gear is $148.36 \text{ kg}\cdot\text{m}^2$.

With the increase of the observation data, the recursive result is more and more stable under the first gear which is betrayed in Figure 7. The final RLSE of the load equivalent inertia on the transmission output shaft under the first gear is $159.49 \text{ kg}\cdot\text{m}^2$. Obviously, there is a difference with $8.04 \text{ kg}\cdot\text{m}^2$ between the final RLSE of the load equivalent inertia and the actual load equivalent inertia on the transmission output shaft under the first gear and the percentage of the estimation error is 4.80%. As time goes on, the estimation difference of the load equivalent inertia is lower, so the value of the estimation accuracy becomes lower that it is only 0.0161 or 1.61% at the end of the estimation in Figure 8. That is to say, the estimation accuracy is more and more stable as time goes on.

As is shown in Figure 9, the acceleration process is longer than that under the first gear. The final RLSE of load equivalent inertia on the transmission output shaft under the third gear is $151.10 \text{ kg}\cdot\text{m}^2$ in Figure 11. As a consequence, the estimation error between the final RLSE and the actual load equivalent inertia is $2.74 \text{ kg}\cdot\text{m}^2$ which is lower than that under

the first gear. The percentage of the estimation error is 1.85%. The estimation accuracy is only 0.0074 or 0.74% at the end of the estimation in Figure 12.

As can be seen, the more the data is, the better the estimation result is. Consequently, the load estimation method is effective. The reasons of the estimation errors can be found from both sides. On the one hand, the pressure fluctuation of the loading device can result in the fluctuation of the load resistance torque. On the other hand, the clutch wear leads to the fitting error of the clutch torque-displacement characteristics.

5. Conclusion

The load parameters estimation methods are studied during AMT startup as the soft starter for belt conveyor in the paper. The main conclusions are as follows. Firstly, the mathematical models of the load parameters estimation are established according to the mechanical characteristics during AMT startup. Secondly, the recursion least squares method of the load inertia is analyzed. Thirdly, based on the clutch torque-displacement characteristics and the test data during AMT startup, the load resistance torque and the load equivalent inertia are identified. The on-line estimation results show that the load parameters can be effectively recognized by the use of the above identification methods of the load parameters which provides the theoretical and experimental evidences to further study the clutch control strategy and the shift schedule for heavy-duty AMT.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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