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Research Article

Fuzzy Adaptive Shift Schedule of Tractor Subjected to Random Load

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In this paper, the low frequency random load of a tractor is presented. Controlled by a theoretical three-parameter shift schedule, the random load would frequently trigger the random shift. Simultaneously, the driving force of the tractor should be consistent prior to and following this shift. Additionally, the higher traction efficiency and improved load utilization rate should be ensured by a choice of a transmission ratio of the tractor power shift transmission. The shift schedule was utilized for the aforementioned problems solution. An innovative method is presented for theoretical shift schedule modification by the fuzzy algorithm, based on the random load standard deviation and the alteration rate of both steady state values of the load and of the throttle position. The simulation results demonstrated that the modified shift schedule could discover the running state of the tractor. By shielding the random shift judgment caused by the random load, the stability of the tractor was ensured. When the shift was required, the schedule could rapidly respond, whereas the tractor driving force did not sustain a sudden alteration. The schedule could also automatically select and maintain the transmission ratio with higher traction efficiency.

1. Introduction

The advantages of the tractor power shift transmission are proven to be that the power of the tractor is not interrupted during shifting. During shifting of the tractor, the latter can run without lifting farm implement. Consequently, the corresponding efficiency is improved. The key technical indicator of shifting is the corresponding stability, without shifting impact and without power interruption. The shift schedule is proven to be prerequisite for these technical indicators to be achieved. Currently, research on automobile shift schedule is proven to be significantly mature, whereas three kinds of research exist, which can be classified as the expert experience [1], theoretical solution [2, 3], and intelligent correction [4–7] research. The intelligent correction method is proven to contribute to performance improvement of various types of vehicles under specific conditions, such as dynamics and economics of a vehicle [8], by gear shift frequency reduction [9] and an improved demonstration of the driver's intention [10], as the most widely utilized. In order to eliminate frequent shifting phenomenon of automobiles, various methods [11–14] have been presented for shift strategy modification. The grounds of these methods were that the power could be interrupted and that frequent gear shifting is caused by the dynamic characteristics of an engine.

The working load application characteristics of the tractor demonstrated special requirements on shift timing and transmission ratio selection. The reason that causes the tractor frequent shift is also different, and the shift law method of modification of automobiles cannot be utilized. The random load constitutes the main factor that affects the stability of a tractor. The prerequisite for power shifting resides in the driving force of the tractor being equal prior to and following gear shifting. In this way, the gear shift impact caused by the theoretical transmission ratio alteration can be avoided. Besides, if the control system complied entirely with the theoretical shift schedule, when the system is adjacent to the theoretical shift surface, the random dynamic loads of the tractor would cause the system parameters to pass through the shifting surface a high amount of times in a short period of time, subsequently leading to frequent random gear shifting.

Gao et al. [15] modified the theoretical shifting schedule of a tractor and claimed that the tractor performance had been improved, whereas no tractor running condition analysis existed prior to and following gear shifting. The cost of these amendments results in being the grounds of a smooth gear shift destruction, leading to tractor driving force inequality prior to and following gear shifting. Inappropriate shift corrections lead to tractor state alteration; the clutch slipping aggravation is proven to be significantly detrimental to gear shifting. Based on random gear shifting and shift impact mechanism analysis, random load fluctuation coefficient, random load steady state value, and throttle rate alteration were proposed for shift schedule amendment. Through fuzzy algorithm utilization for acquisition of correct parameters, the system can demonstrate the tractor operation state avoidance of frequent random gear shifting and normal shift timing preservation.

2. Theory of Three Parameters Shifting Schedule for Tractor Automatic Transmission

The driving force of the tractor should be consistent prior to and following the shift. When the transmission ratio was determined, the vehicle driving force became a function with independent variables of throttle opening (α), tractor speed (v_t), and driving wheel slip rate (δ). With α and δ as definite variables, the shift schedule acquisition could be interpreted as tractor speed acquisition satisfying the shift condition. An equation was determined according to shifting conditions, with the α and δ corresponding speed equation solution, consequently leading to the optimal three-parameter shift schedule being obtained, composed of α, v_t, and δ.

The tractor driving force (F_q) was expressed as

$$F_q = \frac{Me \cdot i_g \cdot i_q \cdot \eta_n}{r_q}, \quad (1)$$

where Me is the engine output torque, i_g is the transmission ratio of the automobile, i_q is the transmission ratio of the other gears in the transmission, η_n is the mechanical transmission efficiency of the transmission system, and r_q is the tractor driving wheel rolling radius.

The relationship between the engine speed (ne) and v_t was expressed by

$$ne = \frac{i_g \cdot i_q \cdot v_t}{0.377 \cdot r_q (1-\delta)}. \quad (2)$$

Also, Me was expressed as

$$Me = \sum_{i=0,j=0}^{i=4,j=4} a_{i,j} \cdot \alpha^i \cdot ne^j, \quad (3)$$

where $a_{i,j}$ are the fitting coefficients, α and δ were set in advance, according to (1), (2), and (3), and the relationship

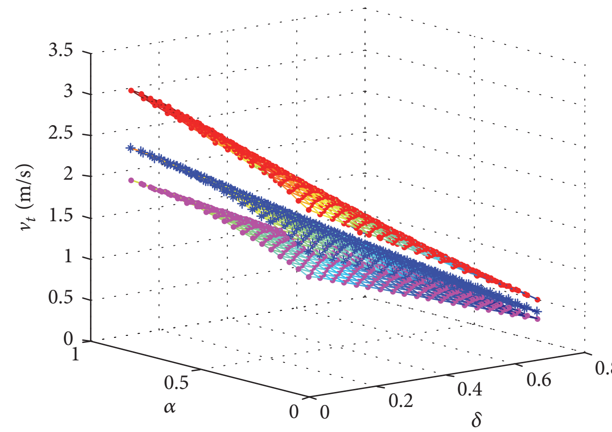

Figure 1: Tractor theoretical shift surfaces.

among F_q, i_g, and v_t was determined. This relationship formula was expressed as

$$F_q\left(i_g, v_t\right) = \sum_{i=o}^{i=4}\sum_{j=o}^{j=4} a_{i,j} \cdot \alpha^i \cdot \left[\frac{i_g \cdot i_q \cdot v_t}{0.377 \cdot r_q \cdot (1-\delta)}\right]^j \cdot i_g \cdot i_q \cdot \eta_n \cdot r_q^{-1}. \quad (4)$$

The transmission ratios of two sequential speeds are expressed as $i_g(n)$ and $i_g(n+1)$. The driving force of the tractor was required to be consistent prior to and following shifting, expressed as

$$F_q\left(i_g(n), v_t\right) = F_q\left(i_g(n+1), v_t\right). \quad (5)$$

Regarding the solution of (5), v_t meeting shifting conditions was solved, as α, δ, $i_g(n)$, and $i_g(n+1)$ variables were known.

In this paper, v_t matching the shifting conditions was labeled as v_s. In Figure 1, the shift schedule point cloud and the corresponding fitting surface of a dongfanghong-2004 tractor is presented.

In Figures 1 and 3, shift surfaces existed and were utilized for conversion determination of 4 transmission ratios ($i_g(1), i_g(2), i_g(3), i_g(4)$). The shift schedule fitting surfaces could be expressed as

$$v_s\left(i_g(n), i_g(n+1)\right) = f(\delta, \alpha) \quad n = 1, 2, 3, \quad (6)$$

where $v_s(i_g(n), i_g(n+1))$ is the threshold of various theoretical shift speed and could be considered as the vertical projection of v_t in the three shifting surfaces and f is a fitting function.

The comparison of both v_t and v_s values could determine whether shifting would be required, as the α, δ, and i_g variables were known.

In Figure 2, an example demonstrating the advantages of (5) shifting definition is presented.

With the assumption of the tillage depth and tractor soil specific resistance being constant and the tractor load not being affected by random disturbance, the throttle opening (α) increased. The red dotted lines in Figure 2 indicated the

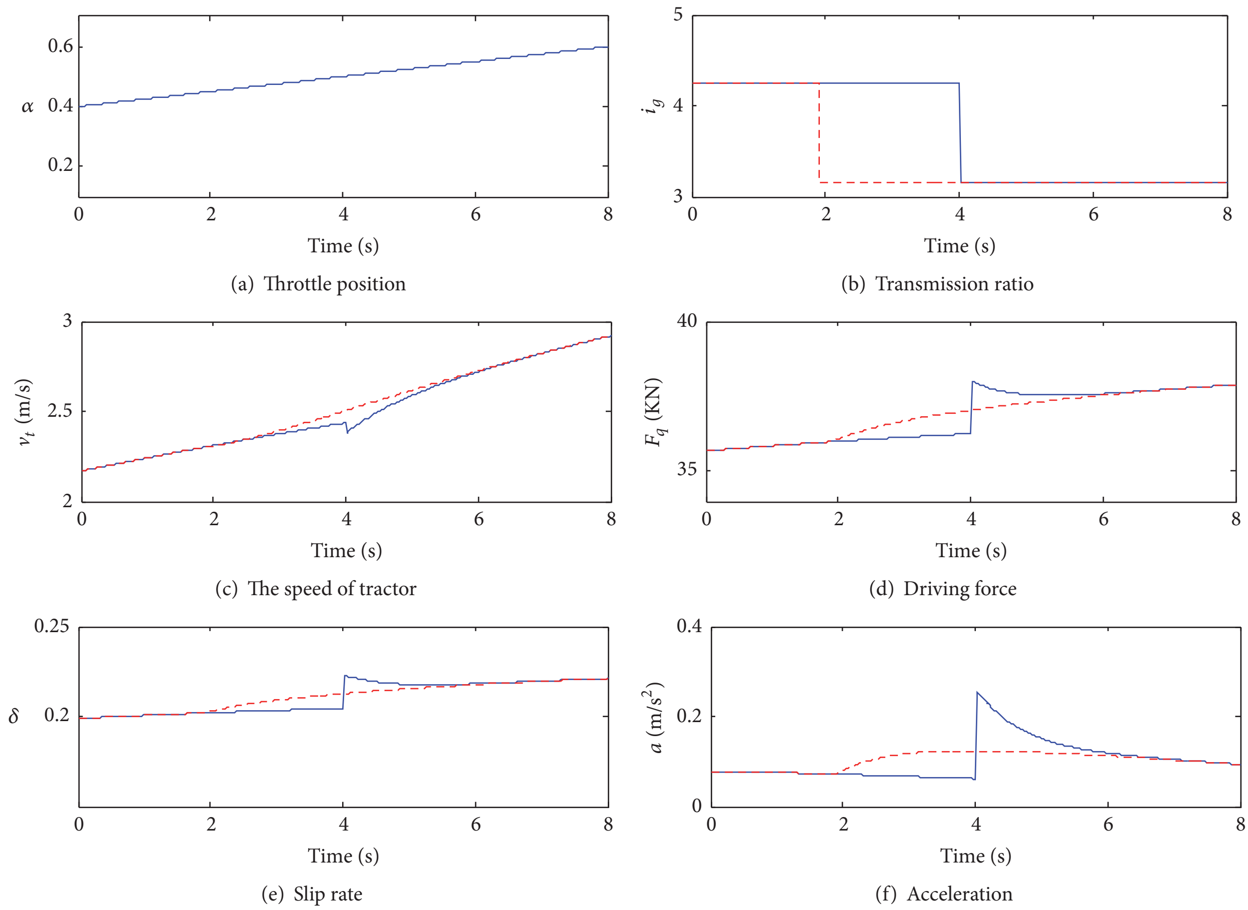

FIGURE 2: Shifting time effects on tractor state.

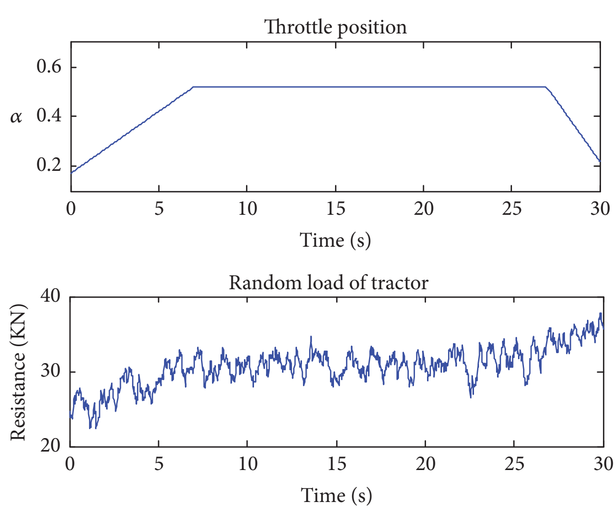

FIGURE 3: Tractor throttle opening (α) and working resistance.

tractor state parameters following the shifting schedule. In contrast, the blue solid lines indicated the tractor parameters which did not obey the shifting schedule. It can be observed from Figure 2 that when the transmission ratio (i_g) was altered, the red dotted lines for Figures 2(b)–2(f) are smooth, which was interpreted that the driving force (F_q), tractor speed (v_t), slip rate (δ), and tractor acceleration (a) are relatively stable following shifting. Also the blue solid lines all demonstrated a significant step alteration during shifting. This would cause shifting impact, thereby affecting driving comfort along with the tractor efficiency.

3. Shifting Rules Fuzzy Adaptive Correction Strategy

3.1. Factors Affecting Tractor Power Shifting Quality

3.1.1. Frequent Gear Shifting Caused by Load Fluctuation. In reality, the load of the tractor is not smooth load but the low frequency random load [16, 17]. The load fluctuation coefficient is related to both tractor speed and soil quality. The throttle opening and working resistance of the tractor are presented in Figure 3.

In the case of high load fluctuations, the tractor state parameters would fluctuate. With the theoretical shift schedule consideration, the fluctuations of the state parameters can trigger random frequent shifting. In Figure 4, frequent shifting caused by random loads is presented.

In Figure 4, the red line represents the theoretical shift speed threshold (v_s). It can be observed that when slip rate

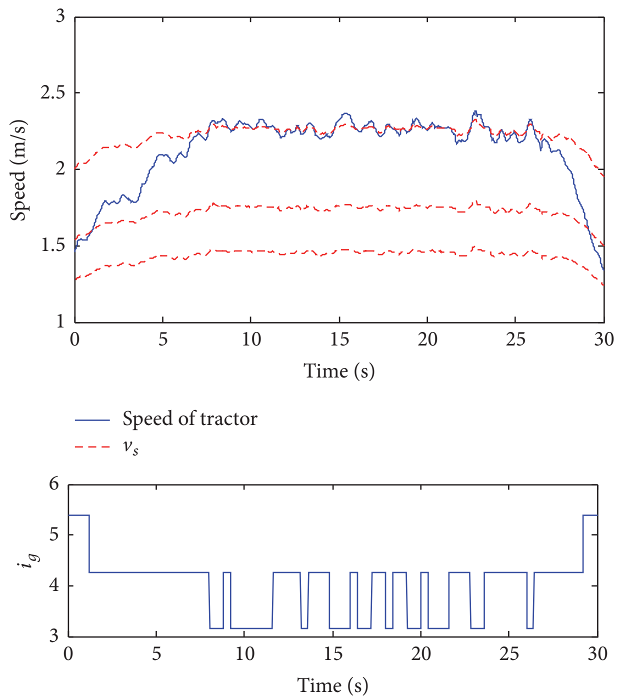

Figure 4: Frequent shifting caused by random load fluctuation.

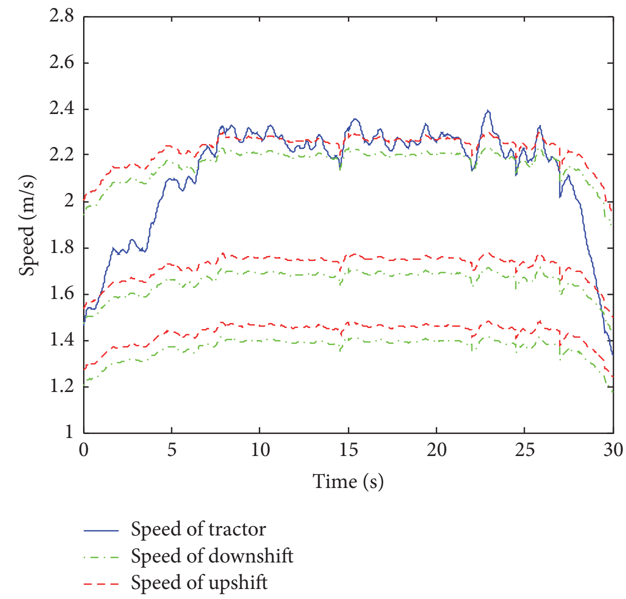

Figure 5: Delay downshift strategy.

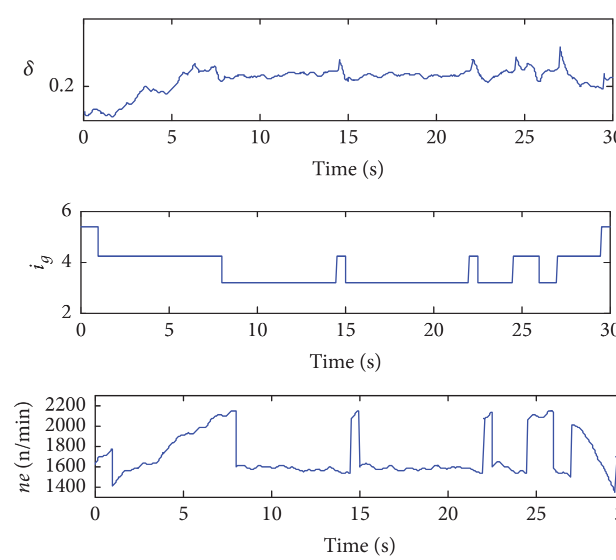

Figure 6: Tractor status controlled by delayed downshifting strategy.

fluctuations occurred, v_s also corresponded to the same direction of fluctuations. This demonstrated that the theoretical shift schedule had certain adaptation ability to fluctuations in the system.

Besides, when the system was in a critical shifting state, both the load and throttle were not apparently altered, whereas the dynamic load fluctuation exceeded the corresponding resistance to fluctuation ability, leading the system to surpass the speed shift line several times, resulting in random shifting.

The traditional way for this kind of random shifting is a delayed downshifting (presented in Figure 5). The upshift rule still obeys the theoretical shifting schedule. The downshift rule is to set the actual downshift speed lower than v_s. The correction speed (Δv) value is generally set to 0.3 km/h~0.5 km/h. As presented in Figure 5, the green line represents the downshift speed curve.

The disadvantages of this method were as follows: the speed drop value was determined in advance, as not adaptable to various working conditions and environment. If the setting value was low, the random shift could not be completely eliminated, whereas if the setting value was too high, shifting would delay, resulting in a sudden driving force alteration and shift quality reduction.

In Figure 6, the tractor status controlled by delaying downshifting strategy is presented. Compared to the theoretical shift schedule, the delayed downshifting strategy of frequent random shifting could be reduced, whereas random shifting could not be completely eliminated. The tractor slip rate as a driving force indicator displayed a sudden alteration during downshifting.

3.1.2. Effects of Shifting Timing on Tractor State during Working Conditions. When the throttle or the external load was rapidly increasing, the tractor state parameter alteration would accelerate. At this time, if an improper shifting occurs, such as advanced and delayed shifting, the tractor driving force, slip rate, and speed would be led to a sudden instantaneous shift alteration, therefore exacerbating the clutch sliding friction and shifting impact. As presented in Figure 6, the phenomenon of abrupt alteration in the slip rate caused by artificially delayed shift is presented.

3.1.3. Effects of Transmission Ratio on Tractor's Traction Efficiency. According to the traditional theory of delayed downshifting, when the system was in the critical shifting point, it was significantly inclined to select the higher speed

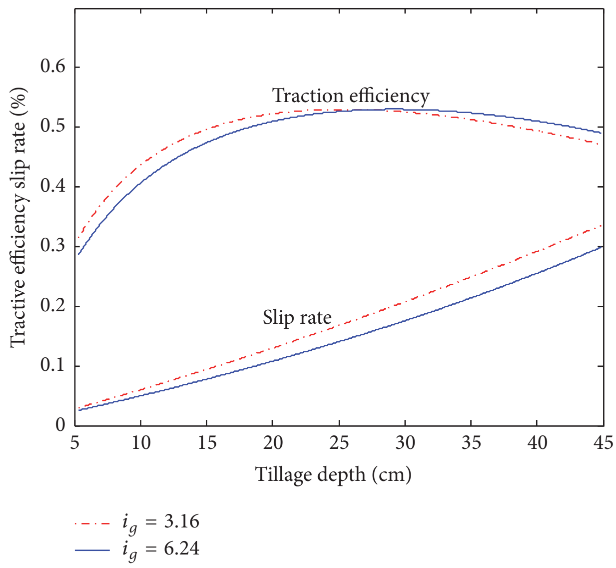

FIGURE 7: Comparison of traction characteristic of tractor.

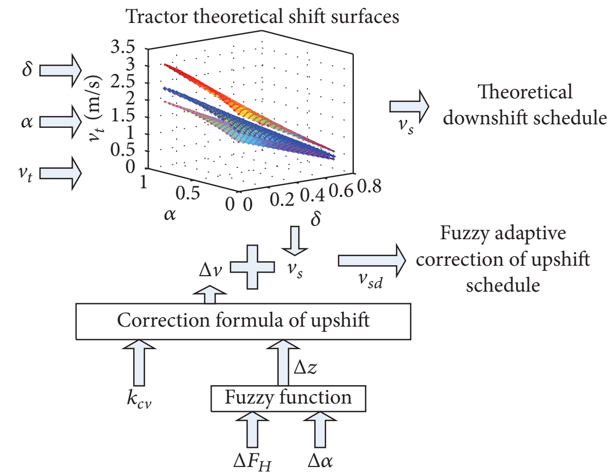

FIGURE 8: Fuzzy adaptive shift schedule correction.

between the two sequential speeds. This method was utilized for the car shifting rule to be dealt with and does not apply to tractors. During field work, the tractor resistance was significantly high, whereas the engine was in a state of heavy load.

Currently, a traction high efficiency of traction can be achieved by the high throttle and high transmission ratio control strategy adaptation. In Figure 7, the traction characteristic curve of the tractor under various transmission ratios of the tractor power shift transmission is presented.

In Figure 7, blue lines and red dashed lines indicate when the transmission ratios were of 6.24 and 3.16, being the corresponding efficiency parameters of the tractor. It can be observed that the tractor slip rate increased as the traction force increased. During the light load stage, the lower the transmission ratio, the higher the efficiency of the tractor. During the heavy load stage, the slip ratio exceeded 0.18; the higher the transmission ratio, the higher the efficiency of the tractor.

3.2. Modification Principle

(1) Regarding frequent shifting caused by the random load, the corrected value of the shift schedule could be altered by load fluctuation; consequently, a complete random shift elimination ability could be presented.

(2) Regarding the shifting caused by the throttle and traction resistance alteration, the shift schedule should not be attempted to interfere with the pure theory law, for smooth shifting to be ensured.

(3) Regarding the light load conditions, the schedule should have delayed downshifting, whereas, for high load conditions, upshifting should have been delayed.

From these three principles, principles (1) and (2) seem to be contradictory. In fact, as long as the control system could accurately distinguish random and proper shifting, the two principles could be aligned when the random shift mechanism was as low throttle alteration and traction resistance in the shifting critical area, and the effects of system alteration were less than the random load effects, this kind of shift should be avoided. Proper shift referred to the external environment alteration constituting the three-parameter system state quick shift schedule surpassing and therefore shifting triggering. At this time, the effects of system alteration went beyond the impact of random loads.

According to the aforementioned analysis, an adaptive delayed shifting method was proposed, which could reflect the system alteration by environmental parameters introduction. The correction principle is presented in Figure 8.

Three environmental correction parameters, the random load fluctuation coefficient (k_{cv}), rate of change of the random load steady state value (ΔF_H), and throttle position change rate ($\Delta\alpha$), could be utilized for system observation. The sampling frequency of the control system sensor signal was 50 HZ and the shift controller determination frequency was 1 HZ. k_{cv} was defined as the random load standard deviation ratio to the load steady state in a shifting calculation period. ΔF_H was defined as the difference between the steady state loads of two sequential shift determinations. The steady state load (F_H) could be obtained by the mean filter. $\Delta\alpha$ was the difference of the throttle opening between two sequential shift determinations.

The shifting schedule correction principle was that the higher the random load fluctuation, the higher the shift schedule alteration, whereas the throttle speed and traction force alteration could offset the load fluctuation correction.

Tractor more often works in a heavy load state, so the control system requires an upshifting modification. The control system required an upshifting modification. When determining if the tractor transmission needs upshifting or not, the control system, according to theoretical shift schedule, can get v_s, which plus the speed correction Δv will make the threshold value of actual shift speed (v_{sd}).

Δv is a function of v_s, ΔF_H, and $\Delta\alpha$ as independent variables, expressed as

$$\Delta v = 1.2 \cdot k_{cv} \cdot v_s \cdot \left[1 - f_{xz}\left(\Delta F_H, \Delta a\right)\right]. \quad (7)$$

Table 1: Fuzzy inference rule.

Δz		$\Delta\alpha$ PB	PS	Z	NS	NB
ΔF_H	PB	S	M	M	S	S
	PS	M	S	S	S	S
	Z	M	S	Z	S	M
	NS	B	B	S	S	M
	NB	B	B	M	M	S

Δv is a value higher than or equal to 0; Δv and k_{cv} are linearly related. It was interpreted that the higher the load fluctuation, the higher the increase and stop delays.

The relationship among Δv with ΔF_H and $\Delta\alpha$ represents the typical nonlinear characteristics. This relationship is related to the combination of both positive and negative values of ΔF_H and $\Delta\alpha$ as along with the combination of these two factors. f_{xz} indicates the system state alteration.

3.3. Fuzzy Controller Design. The nonlinear mapping relation $\Delta z = f_{xz}(\Delta F_H, \Delta a)$ was difficult to be characterized by a specific function expression. The fuzzy algorithm was quite suitable for the solution of this problem.

ΔF_H and $\Delta\alpha$ are the input variables. The linguistic value was set for "negative big" (NB), "negative small" (NS), "zero" (Z), "positive small" (PS), and the "positive big" (PB). The linguistic value of the output variable was "zero" (z) and small (s), "medium" (m) and "big" (b). The fuzzy domain of the output variable was in the range of $[0, 1]$.

Through the tractor dynamic analysis, the following determination could easily be obtained. ΔF_H increased and the speed decreased. When $\Delta\alpha$ increased, the speed increased. When ΔF_H and $\Delta\alpha$ sustained alternation, the system state sustained a fastest alteration; when both ΔF_H and $\Delta\alpha$ changed in the same direction, the system state alteration was relatively low; when ΔF_H and $\Delta\alpha$ were constant, the system was stable.

Due to the upshifting strategy modification requirement, the factors that led to upshifting could be compensated according to system alterations. Regarding the factors that led to downshifting, a low compensation was necessary, whereas the unified output variable linguistic value was set to "small."

According to the aforementioned conclusions, the fuzzy rules are presented in Table 1.

The domain of the fuzzy controller is presented in Figure 9. The system calculated ΔF_H and $\Delta\alpha$ values and sent them to the fuzzy controller; then the fuzzy controller output $\Delta z = f_{xz}(\Delta F_H, \Delta a)$. The control system according to (7) calculated the amount of correction Δv.

Following the upshifting schedule correction, the original shifting schedule was divided into two parts, the theoretical shift schedule being the rule of downshifting, whereas the amendment strategy was applied to the upshifting schedule.

4. Results and Discussion

According to the working conditions of Figure 3, the shifting schedule correction was applied and the simulation results are presented in Figures 10–12.

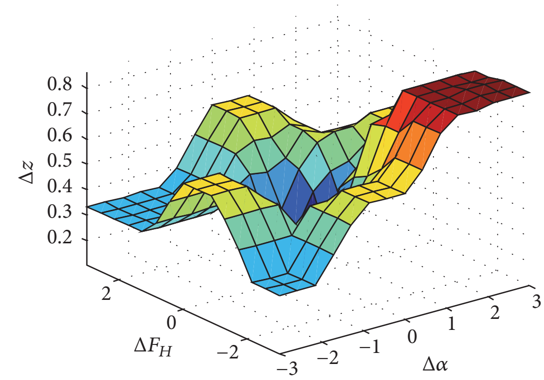

Figure 9: The domain of the fuzzy controller.

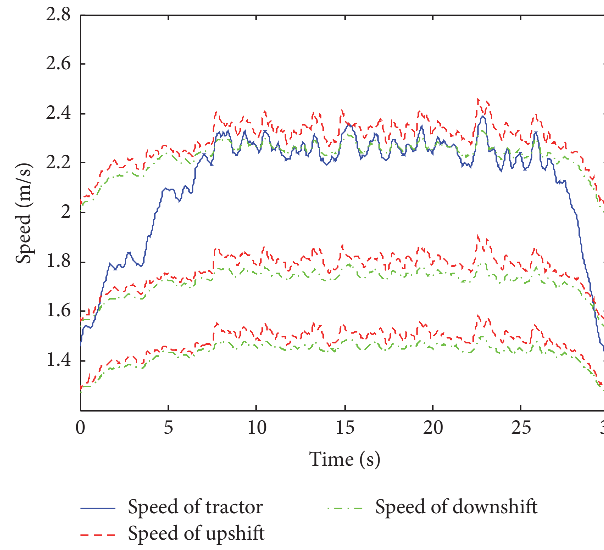

Figure 10: Fuzzy adaptive delay upshifting.

In Figure 10, the blue line is the tractor speed, the red line is the upshifting speed, and the green line is the downshifting speed. Combined with the specific conditions of Figure 3, it can be observed that when the system required rapid shifting, both the upshifting speed and theoretical shifting lines almost coincided. When the system state was adjacent to the shift curve, whereas the state of the system was not altered; the distance between the upshifting speed and theoretical shifting lines was increased; therefore, a random frequent shifting was avoided.

In Figure 11, the blue line represents the tractor state with fuzzy adaptive correction; the red dashed line indicates the tractor status controlled by a delaying downshift strategy. As it can be observed from Figure 11, the tractor presented no random shifting, when controlled by fuzzy adaptive strategy. The slip rate did not change abruptly. Compared to delayed downshifting, the tractor engine of was running at the rated speed and the load degree was improved.

As it can be observed from Figure 12, Δv was not set in advance, whereas combined with the real-time load fluctuations (k_{cv}) and fuzzy controller output (Δz), it could

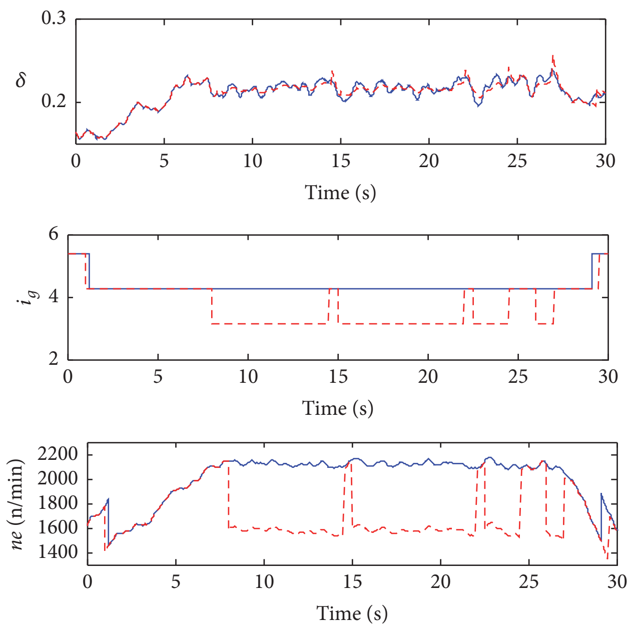

FIGURE 11: Delayed downshifting and fuzzy adaptive correction comparison.

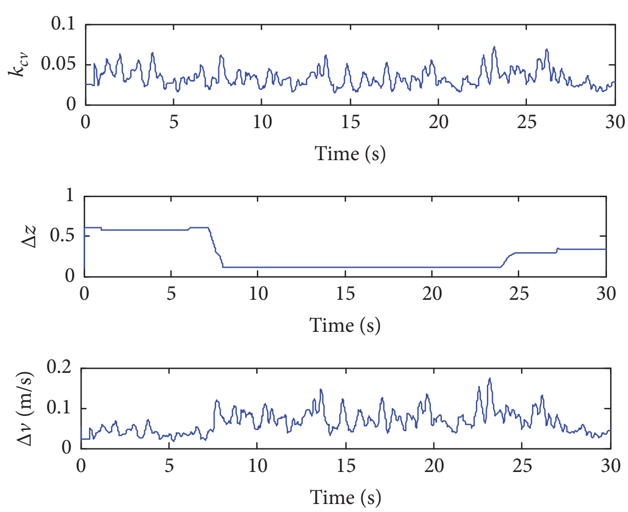

FIGURE 12: Shift schedule real-time adaptive correction for i_g1-i_g2.

be a good response to the external environment abrupt alterations.

5. Conclusions

The tractor load of tractor is a random dynamic load. If the control system of the tractor power shift transmission follows the theoretical shift schedule, it would be incorrect for the shifting timing to be determined due to random load interference, resulting in frequent shifting. In this paper, the traction characteristic curve of a tractor was analyzed, whereas the principle of transmission ratio selection under various conditions was determined. On the basis of frequent shifting factors analysis and effects, in this paper, a method for velocity correction parameters calculation by the fuzzy algorithm was presented, based on random load standard deviation; the alteration rate of the load steady state value and throttle position was analyzed. The simulation results displayed that the modified shift schedule could demonstrate the tractor running state. When the tractor required shifting, the control system could rapidly respond, whereas the tractor driving force could remain stable prior to and following shifting. Simultaneously, the system could also execute an adaptive identification of random shifting conditions and shield the random shift judgment caused by random load and automatically select and maintain the transmission ratio with higher traction efficiency.

Competing Interests

The authors declared that they have no conflict of interests to this work.

Acknowledgments

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