Study on Optimal Power Shift Schedule of Self-propelled Combined Harvester

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Abstract. In terms of the optimal power shift schedule of combined harvesting machinery, in order to improve the accuracy on solving optimal power shift points, this paper deduces the solving method to obtain the optimal power shift law of harvesting machinery based on the analyzing the characteristics of harvesting machinery. Two shift control parameters that have significant impacts on the optimal power shift point of harvesting machinery are put forward in the paper, namely the mass parameter and power distribution parameter. Taking the 4YZ-4-type combined maize harvester as an example, through the numerical calculation of MATLAB, it is found out that the change of mass parameter and power distribution parameters have significant impacts on the optimal power shift point. When the quality of harvesting machinery increases, the speed of the optimal power shift point will increase and the acceleration will decrease. When the power distribution coefficient of the driving axle of the harvesting machine increases, the corresponding speed at the optimal power shift point will decrease and the corresponding acceleration will increase.

1. Introduction

Shift schedule refers to the change schedule of gear position with control parameters, namely the problem of determining shift point\cite{1,2}. The quality of shift schedule directly affects the power, economy and comfort of the vehicle\cite{3}. According to the different objective functions, the shift schedule can be divided into the optimal power shift schedule and the optimal economy shift schedule\cite{4,5}. Considering the bad working environment and wide load variation range of the harvesting machine, in order to improve the power performance of the harvesting machine, the research on the optimal power shift schedule has more practical application value.

The conventional three-parameter optimal power shift law is the basis for solving the optimal power shift point, but it ignores the problems of vehicle mass change and engine power distribution in the process of calculating the shift point, hence it cannot be applied to solving the optimal power shift point of all vehicles\cite{6}. To find out the exact optimal power shift point, many experts and scholars at home and abroad constantly revise the power shift schedule according to the actual situation of the vehicle, and comprehensively consider the influence of various shift control parameters on the shift point under different conditions. According to the characteristics of bus load changes, Li et al put forward the viewpoint of changing load shift schedule, which greatly improved the driving dynamics of the bus\cite{7}; Niu comprehensively considered the influence of road slope, vehicle mass, wind resistance and other parameters on the optimal dynamic shift point, and proposed a correction method for dynamic three-parameter dynamic shift schedule\cite{8}; Fu et al jointly corrected the shift control parameters and gears for the frequent shift of tractors, not only solving the problem of frequent shift of tractors, but also reducing the fuel consumption rate during the turn of tractors\cite{9}; Cong et al put...
forward two kinds of curve shift indexes to solve the problem that the car can't downshift in time when
it is over-curved, and the effectiveness of the proposed curve strategy is proved by real car
experiments[10]; Zhang et al proposed a four-parameter control strategy to increase the rate of change
of throttle opening in view of the frequent shift of construction vehicles. The simulation comparison
with the three-parameter shift schedule proves the superiority of the proposed method[11]; according to
the problem of insufficient power on vehicle uphill, Chen et al corrected the uphill shift schedule
based on the analysis of engine characteristics, and proved the reliability of the method through
experiments and simulations[12].

Through the above analysis, it can be found that although a great deal of research results have been
made on the modification of the optimal power shift schedule of three parameters, most of the
modification methods are mainly for conventional vehicles such as passenger cars and commercial
vehicles, and few studies have been made on the optimal power shift schedule of harvesting machinery.
Whether it is from the working environment or from the working characteristics, there are great
differences between the harvesting machinery and the conventional vehicles, hence there must be
many differences in the shift schedule. By analyzing the working characteristics of harvesting
machinery, this paper proposes two shift correction parameters for harvesting machinery, and studies
the influence characteristics of the two parameters on the optimal dynamic shift point through
theoretical calculation.

2. Principle of optimal power shift schedule
The optimal power shift schedule is a shift control method that enables the vehicle to shift gears at the
optimal power shift point to improve the power performance of the vehicle. According to the
definition of the optimal power shift schedule, in order to ensure the optimal power performance of the
vehicle, the intersection of the acceleration curves of two adjacent gears at the same throttle opening is
the optimal power shift point[13], which can be solved by the following equation:

\[ a \big|_n = a \big|_{n+1} \] (1)

Thereinto, \( a \) represents acceleration; Subscript \( n \) and \( n+1 \) means that the gear of the harvester is in
the \( n^{th} \) gear and \( n+1^{th} \) gear, respectively.

By analyzing the longitudinal kinematics of the harvesting machine, the acceleration \( a \) in the
direction of movement of the harvesting machine can be expressed as the following equation:

\[ a = \frac{F_t - F_r}{\delta_m m} \] (2)

Thereinto, \( F_t \) is the driving force of the harvester; \( F_r \) is the resistance during the driving of the
harvester (excluding acceleration resistance); \( \delta_m \) is the conversion factor of the rotating mass of the
harvester; \( m \) is the total mass of the harvester.

The driving force of the harvesting machine is the reaction force generated by the interaction of the
the torque distributed by the drive wheel with the ground. According to the function superposition
method[14], the engine output torque can be expressed as a function of the throttle opening degree and
the engine speed, specifically as the followings:

\[ M_x(n_\alpha, \alpha) = M_1 + M_2(n_\alpha) - M_3(n_\alpha, \alpha) \] (3)

\[ M_1 = \frac{M_{em} + M_{e0}}{2} \] (4)

\[ M_2(n_\alpha) = \frac{M_{em} - M_{e0}}{2} \sin \left[ \frac{\pi}{2} \left( 1 + \frac{n_\alpha - n_{e0}}{n_{e0} - n_{emin}} \right) \right] \] (5)

\[ M_3(n_\alpha, \alpha) = \frac{b \cdot n_{e0}}{\alpha(n_{emax}(\alpha) - n_\alpha)} \] (6)
Thereinto, $M_{\text{em}}$ is the maximum torque of the engine; $M_{\text{e0}}$ is the rated torque of the engine; $b$ is the slope correction coefficient; $\alpha$ is the throttle opening; $n_e$ is the engine speed; $n_{\text{em}}$ is the corresponding speed at the maximum torque; $n_{\text{e0}}$ is the rated speed; $n_{\text{emax}}(\alpha)$ is the highest no-load speed of the engine when the throttle opening is $\alpha$.

The torque output by the engine equipped with the harvesting machine is used to drive the harvesting machine to work, and it makes the working parts work normally, among which the working parts mainly include the harvesting table, the conveying device, the peeling machine, the returning device, etc. According to the calculation and analysis, it finds out that the power of the engine consumed by the working device accounts for more than 50% of the total output power of the engine during the normal field harvesting operation, which is quite different from that of conventional vehicles\cite{15}.

According to the relationship between the output torque of the harvester and the driving force of the harvester, the driving force at the $t$ gear of the harvester can be expressed as follows:

$$F_t = \frac{M_e(n_e, \alpha)\eta_{T}i_{g,t}i_{0,i}i_{m}\eta_{\eta}}{\eta_{\alpha}}$$  (7)

Thereinto, $F_t$ is the driving force of the harvester, $M_e(n_e, \alpha)$ is the engine output torque, $i_{g,t}$ is the transmission ratio of the transmission at $t$ gear, $i_0$ is the main reducer transmission ratio, $i_m$ pulley transmission ratio, and the harvester is mostly equipped with a stepless transmission device in the clutch to realize high and low speed conversion, hence $i_m$ is divided into $i_{\text{max}}$ and $i_{\text{min}}$ respectively corresponding to high and low speed pulley transmission ratios. $r$ is the radius of the driving wheel, and most harvesting machines are driven by the front wheel. $\eta_{T}$ is the mechanical efficiency of the drive train; $u$ is the drive axle power distribution coefficient.

Considering the low operating speed and small field slope of the harvesting machine, the influence of air resistance and ramp resistance on the movement behavior of the harvesting machine can be ignored, hence the driving resistance of the harvesting machine mainly includes acceleration resistance and rolling resistance, which can be expressed in the following forms:

$$F_r = mgf$$  (8)

Thereinto, $f$ is the rolling resistance coefficient, and its size is mainly related to road conditions.

Through the above analysis, the concrete form of the equation for solving the acceleration of harvesting machinery can be established as follows:

$$a = \frac{M_e(n_e, \alpha)\eta_{T}i_{g,t}i_{0,i}i_{m}\eta_{\eta}}{\eta_{\alpha}}\cdot u - mgf$$  (9)

### 3. Numerical calculation

This paper takes 4YZ-4 combined corn harvester as the research object. The weight of the corn harvester is about 4500kg, the volume of the ear box is 2.5m³, and the radius of the driving wheel is 0.665m. Equipped with Weichai WP4G165E330 engine with rated power of 120kw. The rated speed is 2300r/min, and the specific parameters are shown in Table 1. Equipped with Weihe WH300-416000 four-speed transmission, including 3 forward gears and 1 reverse gear, each gear speed is shown in Table 2. In addition, the transmission ratio of the final reducer is 6.07, the transmission ratio of the pulley in the low speed state is 1.5, the transmission ratio of the pulley in the high speed state is 1, and the transmission efficiency of the whole transmission system is 0.85.

| Speed (r·min⁻¹) | 800  | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 | 2400 |
|-----------------|------|------|------|------|------|------|------|------|
| Torque (N·m)    | 430  | 496  | 568  | 600  | 599  | 598  | 561  | 522  |

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Table 2. Transmission ratio of each gear.

| Gear position | Gear 1 | Gear 2 | Gear 3 | Reverse gear |
|---------------|-------|-------|-------|--------------|
| Speed ratio   | 22.644| 9.403 | 3.412 | 10.536       |

Using the numerical calculation function of MATLAB, the influence characteristics of mass parameters and power distribution parameters on the optimal dynamic change point are studied by compiling the engine output torque calculation subroutine and the optimal dynamic change point calculation subroutine.

3.1 Influence of quality parameters on optimal power shift point

Most of the self-propelled combined harvesting machines are equipped with a certain volume of ear boxes. After the harvesting machines complete the task of harvesting crops, crops need to be stored and transported. This means that the quality parameters of the harvesting machines are constantly changing in the process of work. The changing schedules of the quality parameters are affected by many factors such as operating speed, operating width, crop density and moisture content, which will not be discussed in detail here. Since the full load mass of the ear box accounts for over 20% of the whole machine mass, the change of the mass parameters will have an impact on the optimal shift point of the harvesting machine.

Figure 1. Acceleration curve of gears 1 and 2 with different mass parameters.

![Figure 1](image1.png)

Figure 2. Curve of speed and acceleration versus mass parameter at optimal dynamic shift point.

![Figure 2](image2.png)

When the mass parameters change, the changing characteristics of the optimal power shift point of the harvester are studied. As can be seen from Fig.1, the acceleration curve of the harvester will also change after the mass parameters of the harvester are changed. When the mass parameters of the harvester increase, the acceleration curve of the harvester will decrease, resulting in the acceleration decrease after the speed of the shift point is delayed. Fig.2 is a graph for extracting the optimal power shift point under different mass parameters separately. It can be seen from Fig.2 that the speed corresponding to the optimal power shift point increases linearly, and the acceleration corresponding to the optimal power shift point does decrease linearly with the increase of the mass parameters of the harvester.

3.2 Influence of drive axle power distribution coefficient on optimal power shift point
During the field operation of the harvesting machine, the drive axle only shunts part of the power of the engine. With the change of working conditions, the power distribution ratio between the working device and the drive axle fluctuates within a larger range. When the harvester is in normal working condition, to meet the normal power demand, the split power of the working device accounts for about 40% to 60% of the total power of the engine. When the harvester is in an abnormal working condition, for example, when the harvester is in a field turn-around condition, the shunt power of the working device will be greatly reduced and the power ratio of the drive axle will be greatly increased. Through the above analysis, it can be found that the drive axle power distribution coefficient fluctuates greatly under the influence of various factors when the harvester is operating in the field, and only part of the engine output power of the harvester is input to the drive axle to drive the harvester to travel, which is quite different from that of the car whose main purpose is to travel.

When the power distribution parameters of the drive axle change, the changing characteristics of the optimal power shift point of the harvester are studied. As can be seen from Fig.3, when the power distributed by the drive axle of the harvester decreases, the acceleration curve of the harvester decreases, causing the intersection of the acceleration curves of the two adjacent gears to change accordingly. Fig.4 specifically shows the characteristics of the speed and acceleration corresponding to the optimal power shift point as a function of the drive axle power distribution coefficient. When the drive axle power distribution coefficient increases, the speed corresponding to the shift point decreases and the corresponding acceleration increases, and the speed and acceleration of the shift point show a good linear relationship with the drive axle power distribution parameter. Through the above analysis, it can be found that the change of the power distribution coefficient will have a significant impact on the optimal power shift point of the harvester. Therefore, the power distribution coefficient needs to be taken as an important shift control parameter to improve the power performance of the harvester when making shift schedule.

3.3 Mass parameters and power distribution coefficient of the drive axle affect jointly
In the actual harvesting process, both the quality parameters and the power distribution parameters are always in a changing state. As for the quality parameters, the harvester carries out the field harvest
operation under non-load condition, and its quality parameters increase continuously before full load. Although the variation law of the quality parameters with time is a complex parameter determined comprehensively by many factors such as crop density, traveling speed, etc., it shows an overall upward trend. In contrast, the change schedule of power distribution parameters is difficult to predict. Because of the complex dynamic process in the field operation, the harvester is always in an accelerated or decelerated state in order to cope with the complex and changeable environment in the field, we cannot know the state of the harvester at the next moment, hence we cannot accurately predict the change trend of power distribution. Through the above analysis, it is not difficult to find that the quality parameters and power distribution parameters will jointly affect the optimal power shift point during the operation of the harvester. Thus, studying the influence characteristics of the quality parameters and power distribution parameters on the group's most power shift point can better reflect the real operation state and has more practical value.

Figure 5. Curve of optimal dynamic shift point speed with mass parameters and power distribution parameters.

Figure 6. Curved surface of acceleration of optimal dynamic shift point as a function of mass parameters and power distribution parameters.

When the mass parameters and the power distribution parameters change simultaneously, the changing characteristics of the optimal power shift point of the harvester are studied. As can be seen from Fig.5, when the harvester is in the no-load state and the power factor of the drive axle is 100%, the harvester has the lowest shift point speed. With the increase of the mass parameters and the decrease of the drive axle power distribution parameters, the speed of the shift point of the harvester is also increasing. When the harvester reaches the full load state and the drive axle power distribution coefficient is 40%, the speed of the shift point of the harvester is delayed to the maximum value. Fig.6 shows the relationship between the acceleration at the shift point and the change of the mass parameter and the power distribution parameter of the drive axle. It is not difficult to find from the graph that when the harvester is fully loaded and the power distribution of the drive axle is lowest, the acceleration at the shift point of the harvester has a minimum value. with the decrease of the mass parameter and the increase of the power distribution parameter, the acceleration at the shift point gradually increases, and this change trend of the acceleration at the shift point is just the opposite of the change trend of the speed at the shift point.
4. Conclusion
This paper deduces the optimal power shift law of harvesting machinery, analyzes the influence of mass parameters and power distribution parameters on the optimal power shift point of harvesting machinery, and finds out through calculation and analysis that when the mass parameters increase, the corresponding speed of the optimal power shift point increases and the corresponding acceleration decreases. When the power distribution coefficient of the drive axle increases, the speed corresponding to the optimal power shift point decreases and the corresponding acceleration increases. When the mass parameter and the power distribution parameter change together, the harvester is in non-load state and the driving axle distributes all engine power, the speed corresponding to the optimal power shift point is the smallest and the corresponding acceleration is the largest. With the increase of the mass parameter and the decrease of the power distribution coefficient, the speed corresponding to the shift point gradually increases and the corresponding acceleration gradually decreases.

Therefore, the quality parameters and power distribution parameters are important shift control parameters of harvesting machinery. In the process of formulating the shift schedule of harvesting machinery, the influence of the quality parameters and power distribution parameters on the shift point should be considered comprehensively to meet the requirements of optimal power shift of harvesting machinery.

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References
[1] Xing W J, Yang B K. Research on Automatic Transmission Shifting Rules of Domestic Situation[J]. Equipment Manufacturing Technology, 2014(3):283-286.
[2] Zhang P, Zhang X, Li B, et al. An Inquiry into the Development Situation and Trend of Tractor Automatic Transmission[J]. Journal of Agricultural Mechanization Research, 2017, 39(11):217-222.
[3] Guan L J, Zhang T Z, Ma Y Z. Shift Schedule of Automatic Transmission of Construction Vehicle Based on Matlab/Simulink[J]. Journal of Qingdao University, 2016, 31(1):89-93.
[4] Peng H W, Ren P, Ma K K, et al. Economic Shift Prompt Theory and Its Simulation[J]. Journal of Shandong Jiaotong University, 2015(1):15-20.
[5] Xue D, Zhong X, Li D, et al. Study on the Comprehensive Shift Schedule of Bus with Automatic Transmission[J]. Mechanical Science & Technology for Aerospace Engineering, 2014, 33(3):413-418.
[6] Hou L, Guan D, Huang H T, et al. Study on overall shift rules for engineering vehicles[J]. Chinese Journal of Construction Machinery, 2013,11(3):195-199.
[7] Li H, Wu X C, Zhang J C. Modification to AMT Shifting Schedule for Optimal Power Performance Based on Variable Load[J]. Control Engineering of China, 2015(1):50-54.
[8] Niu Q Y. Modifying 3-parameter optimal-power shift schedule[J]. Journal of Xian University of Science & Technology, 2010(5):593-598.
[9] Ran F, Zhou Z L, Guo Z Q, et al. Research on automatic shift schedule of tractor based on turn-row[J]. Journal of Chinese Agricultural Mechanization, 2016, 37(4):181-184.
[10] Cong X Y, Wang Z C, Cheng J. Self-adaptive curve gear-shifting strategy for automatic transmission vehicles[J]. Journal of Zhejiang University, 2016, 50(8):1570-1577.
[11] Zhang Y M, Xu J, Tian J Y. Four parameters shift strategy of engineering vehicles based on fleetness changing of throttle opening[J]. Mechanical & Electrical Engineering Magazine, 2015, 32(11):1489-1493.
[12] Chen F, Fang Z, Cui G. Application Study of Shifting Schedule on Uphill Mode[J]. Journal of XiHua University, 2017, 36(2):55-60.
[13] Jiang M H, Liu Y B, Chen X, et al. On Optimal Power Performance Shift Schedule of Multifunctional Engineering Vehicle[J]. Journal of Military Transportation University, 2014, 16(5):58-61.

[14] Zhang M Z, Zhou Z L, Xu L Y, et al. Continuous mathematic model for governing characteristics of diesel engine[J]. TRANSACTIONS OF THE CHINESE SOCIETY OF AGRICULTURAL ENGINEERING, 2004, 20(3):74-77.

[15] Zhao N, Diao H G, Chang J G. The Self-propelled Type Corn Combine Harvesters Energy Consumption Analysis and Energy-saving Technology[J]. Journal of Agricultural Mechanization Research, 2013(8):50-53.