DEVELOPMENT AND TEST OF SPEED CONTROL SYSTEM FOR COMBINE HARVESTER THRESHING AND CLEANING DEVICE
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联合收获机脱粒滚筒与清选风机速度调控系统设计与试验

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***Keywords:** combine harvester, threshing cylinder, cleaning fan, speed control*

ABSTRACT

Aiming at real time rotation speed control of threshing drum and cleaning fan for combine harvester, a stepless speed regulation mechanism was developed. Test show that the adjustable range of fan was 600～1150 r/min, average adjustment speed was 9.2 r/s, the absolute error of stable speed was less than 0.72 r/min. The average speed response time was 1.33s, the overshoot was less than 8 r/s. The adjustable range of the drum was 700～1100 r/min and the average adjustment speed was 2.1 r/s. The absolute error of stable speed did not exceed 0.62 r/min, and the maximum relative deviation was 0.38%.

摘要

针对联合收割机脱粒滚筒和清选风机转速实时控制问题,研制了一种无级调速系统.试验表明,风机的调速范围为 600～1150 r/min,平均调节速度 9.2 r/s,稳定转速的绝对误差小于 0.72 r/min.平均转速响应时间为 1.33s,超调量小于 8 r/s.风机转速的可调范围为 700～1100 r/min,平均调节速度为 2.1 r/s,稳定转速绝对误差不超过 0.62 r/min,最大相对误差为 0.38%.

INTRODUCTION

Combine harvester is mainly used for harvesting rice, wheat, corn, millet and other grain crops as well as some cash crops such as rape and soybean. It can complete several procedures such as cutting, threshing, separating, cleaning, bagging or unloading grain in one go in the field. The technical development level of the combine harvester is an important symbol of the degree of agricultural modernization *(Liang Z. et.al, 2018; Ryszard M. and Ewelina J., 2016; Ma Z. et al, 2015)*. The harvesting capacity of the combine harvester is mainly determined by the threshing and separating capacity, which determines the level and performance of the combine harvester and is the core working part of the combine *(Guan Z. et al, 2016; Li Y. et al, 2015; Lenaerts B. et al, 2014)*. As the "digestion system" of the combine harvester, the performance of the cleaning device affects the working performance and efficiency of the whole machine directly. Cleaning device remove the residual impurities such as glume, broken spikes, short stalks from the separated mixture after threshing so as to obtain clean grains. The impurity content and loss rate of the cleaned grains are also the main indexes for measuring the product quality of the combine harvester *(Wang L. et al, 2016; Guan Z. et al, 2019; Xu L. et al, 2019)*.

The loss rate of combine harvester is mainly related to the structural parameters and working parameters of threshing and cleaning device *(Wan X. et al, 2018)*. Among which the rotational speed of threshing cylinder and cleaning fan greatly affect the loss rate *(Badretdinov I. et al, 2019).* For the threshing cylinder, its speed generally no longer changes after setting according to experience. But the feeding amount, crop moisture content, etc. will affect the power of the threshing system. Affected by these random factors, the drum speed would deviate from the set value, resulting in the increase of harvest loss *(Li Y. et al, 2013 and Tang Z. et al, 2012)*. The speed of cleaning fan affects the impurity content and cleaning loss. If the wind speed is too small, the increase of impurity content is high, and if the wind speed is too large, the loss rate is high.

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Harvest loss, grain damage and impurities are complex multiple input multiple output relationship with threshing cylinder speed and cleaning fan speed *(Liang Z. et al, 2019)*. In order to obtain the best correspondence among them, comparative experiments under different parameters need to be carried out. At the same time, the operating parameters need to be adjusted by the intelligent control system according to the working conditions. *(Myhan R. and Jachimczyk E., 2016)*.

The optimal model and intelligent regulation system both depend on the regulation of the cylinder speed and cleaning fan speed (*Toshikazu M., and Tatsuro S., 2017*). The power of combine harvester cylinder and cleaning fan are too high to be driven directly by motors. The hydraulic system has enough power, but adding a hydraulic system on combine harvester is very complex. The transmission system of the original harvester can't be changed with complex structure due to the production cost. Facing the above-mentioned problems, a mechanical stepless speed regulation mechanism for combine threshing cylinder and cleaning fan was designed. The working performance was tested in an experiment. It provided a reference for efficient and low-loss operations of combine harvesters.

MATERIALS AND METHODS

Test Platform

The speed control system for combine harvester threshing and cleaning device was developed based on 4YZ-6T combine harvester. The main parameters of combine harvester are shown in table.1.

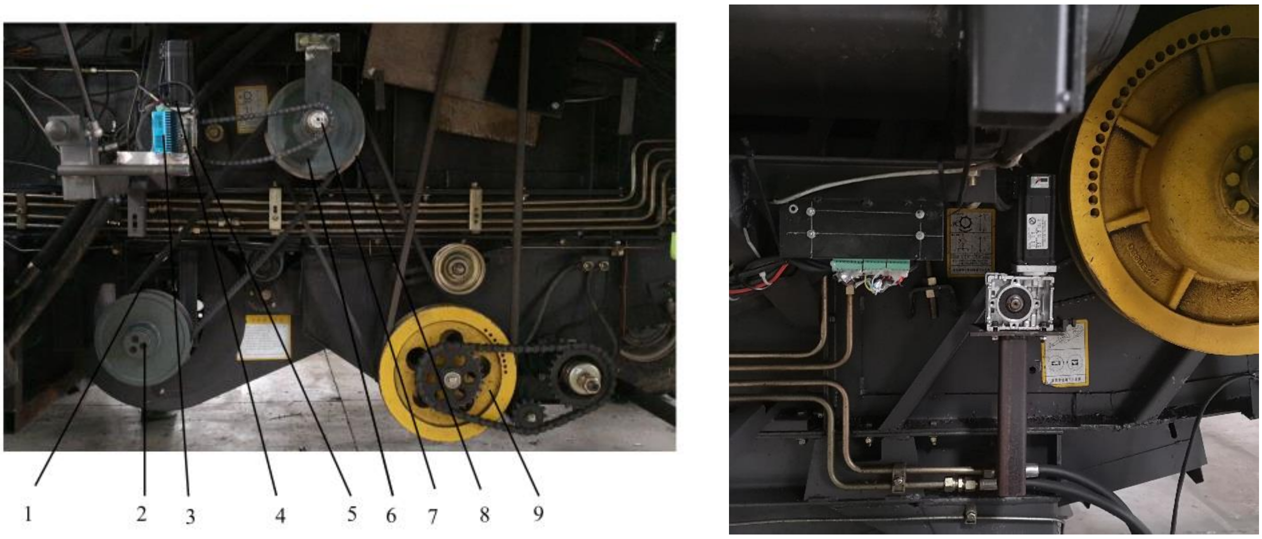
Table 1

Main parameters of combine harvester

Items	Parameters	Items	Parameters
Rated power [kw]	118	**Cleaning fan form**	Centrifugal
Machine quality [kg]	6 450	**Number of fans**	1
Header width [mm]	2 750	**Fan dimensions [mm]**	450
Feed rate [kg·s^{-1}]	≤6	**Operating speed [km·h^{-1}]**	1.6 ~ 7.2
Cylinder dimensions (diametre×length) [mm]	550×3230	**Cylinder type**	Longitudinal axial with nail
Concave clearance [mm]	15 ~ 40	**Productivity [hm^2·h^{-1}]**	0.7 ~ 1.5

Structure and Working Principle

Parts are as shown in figure 1a. The fan speed stepless regulation system includes a pair of stepless speed regulation pulleys, a transmission pulley, a stepper motor and a turbine worm reducer. The stepless speed regulation pulley includes a driving wheel and a passive wheel. The system works as follows: The power output pulley transmits the speed to the drive pulley. The driving wheel and driven wheel of stepless speed-adjusting pulley move coaxially with the same speed. The driving wheel transmits power to the driven wheel through a belt, which drives the cleaning fan to rotate. When speed adjustment is needed, the stepper motor drives the sprocket through the reducer, rotates the speed adjustment mechanism on the driving wheel, and adjusts the belt pulley spacing of the driving wheel. The inside of the pulley is inclined, and the belt width is constant. The actual transmission diameter of the pulley can be changed with the opening and closing of the pulley. Rotating the stepless speed governor of the drive pulley can change the distance between the drive pulley belts. Because the transmission centre distance is constant, when the drive pulley belt distance decreases, the drive diameter of the drive pulley increases and the belt tension increases. As the belt tension increases, the force of the belt compressing the inner wall of the driven pulley increases, the distance between the driven pulleys increases, and the actual transmission diameter decreases. The transmission diameter of the driving wheel increases and the diameter of the passive transmission decreases, while the transmission ratio increases. Similarly, when the distance between the belt pulleys of the driving wheels increases, the driving diameter of the driving wheels decreases, the diameter of the passive driving increases, and the transmission ratio decreases. The change of the transmission ratio is continuously adjustable, which realizes the continuously variable transmission. The principle of the threshing cylinder speed regulating device is the same as the one of the cleaning fan, which is shown in figure 1b.



a) b)

Fig. 1 - Stepless speed regulating mechanism

1 – cleaning fan; 2 – stepless speed regulation pulleys passive wheel; 3 – driver; 4 – stepper motor; 5 – reducer; 6 stepless speed regulation pulleys driving wheel; 7 – sprocket; 8 – drive pulley; 9 – power output pulley

Control model

Firstly, the kinetic model of the threshing drum rotary motion needs to be established. The threshing drum is a variable mass system, and the dynamic model of the drum is established from the angle of energy conservation.

$$\frac{d\omega}{dt}=\frac{N}{J\omega}-\frac{1}{J}\left(A+B\omega^2\right)-\frac{q\omega R}{2\left(1-f\right)J}\cdot\frac{\gamma+\lambda}{1+\gamma} \tag{1}$$

$$q=H\rho v \tag{2}$$

Where:

ω is angular velocity of thresh drum, r/min; J、R、f are rotary inertia of the drum, equivalent radius and rubbing coefficient; v is the combine harvester speed, m/s; H is cutting width, m; N is power provided by the engine to the drum, J; ρ is crop density, kg/m^3; γ is ratio of grain to grass; A is friction coefficient of motion; B is air resistance coefficient; λ is ratio of grain export velocity; q is feed quantity, kg/s.

The efficiency and effect of cleaning fan are determined by the air flow and the size of the fan outlet. Under the excitation force of the fluid, the centrifugal fan:

$$[\boldsymbol{M}]\left\{\ddot{X}(t)\right\}+[\boldsymbol{C}]\left\{\dot{X}(t)\right\}+[\boldsymbol{K}]\left\{X(t)\right\}=\left\{F(t)\right\}+\left\{Q(t)\right\} \tag{3}$$

Where:

$[\boldsymbol{M}]$, $[\boldsymbol{C}]$, $[\boldsymbol{K}]$ are mass matrix, damping matrix and stiffness matrix of the system respectively; $\{F(t)\}$ is the fluid excitation force; $\{Q(t)\}$ is the centrifugal force generated when the impeller rotates; $\{X(t)\}$ is the system displacement vector.

The threshing drum and cleaning fan are controlled by PID control algorithm. PID control technology is more mature in control engineering, has formed a whole set of PID control methods. It can be applied not only to control systems whose mathematical models are known, but also to nonlinear system processes that are difficult to determine for most mathematical models. PID control has merit of simple structure, easily adjusting parameters, as well as good controlling effect. Since the roller motion equation is a nonlinear differential equation, the system has time delay and inertia, crop density is a random variable, and some parameters of the system are also uncertain, so the system is an uncertain nonlinear random system, and PID control is more suitable.

The control law is:

$$u(t)=K_p\left[e(t)+\frac{1}{T_i}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}\right]=K_pe(t)+K_i\int_0^t e(t)dt+K_d\frac{de(t)}{dt} \tag{4}$$

where:

K_p is proportional coefficient; T_i is integral time constant; T_d is differential time constant; K_i is integral coefficient; K_d is differential coefficient.

The transfer function is

$$G(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{5}$$

The differential proportional time constant T_N is introduced

$$G(s) = K_p\left(1 + \frac{1}{T_i s} + \frac{T_d s}{1 + T_d s / T_N}\right) \tag{6}$$

Since the actual signal is discretized, discrete PID control is adopted *(Jumiyatun J. and Mustofa M., 2018)*, so the actual control model of the system is

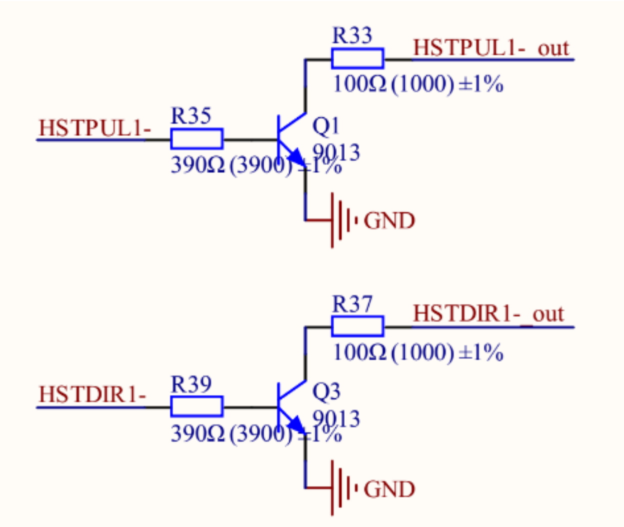
$$u_k = K_p e_k + K_i \sum_{j=0}^{k} e_j + K_d\left(e_k - e_{k-1}\right) \tag{7}$$

where:

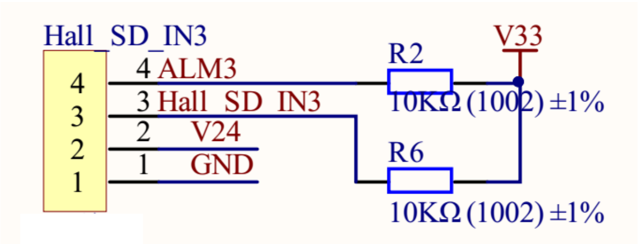
k is sampling serial number; u_k is computer output; e_k is input deviation; T is sampling period.

Control System

The control system includes speed detection and motor control. The control system is mainly composed of STM32 processor, core circuit, power circuit, and motor drive circuit, speed monitoring circuit, CAN communication circuit and reserved interface. The STM32 processor is the information processing and computing centre of the entire speed regulation system. On the one hand, it is responsible for analysing the instructions issued by the main controller and controlling the speed-adjusting drive motor; on the other hand, it reports the current drum fan speed information regularly. The core circuit is the most basic circuit required for the normal operation of the STM32 processor. The power supply circuit provides power for the entire single driver operation. The motor drive circuit is mainly used to transfer the control signal of the cylinder and fan speed control motor as shown in Figure 2a. The speed monitoring circuit supplies the Hall sensor and reads the Hall sensor signal as shown in Figure 2b. Data exchange between stepper motor driver and main controller is made through CAN bus. The reserved interface is the basic IO port on the STM32 processor, which is mainly for the convenience of later function expansion. During the harvesting operation, the main controller sends the speed signals of threshing drum and cleaning fan to the CAN bus. The Hall sensors collect the speed signals of the drum and the fan. Each motor driver filters out the speed instructions for the CAN message and analyses the speed after the signal, configuring the timer to output a specific control signal to drive the motor to rotate.



a. Stepper motor drive



b. Speed monitoring

Fig. 2 - Key circuit

RESULTS

Speed regulation test

The adjustable range of the fan speed is tested as shown in figure 3. The adjustable range of fan speed is 600～1150 r/min, the time from the lowest speed to the highest speed is 59.7s, and the average adjustment speed is 9.2 r/s. The acceleration curve of the fan can be fitted as y=0.1153x-64.691, R^2=99.17%, and the deceleration curve of the fan can be fitted as y=-0.1138x+122.82, R^2=99.15%.

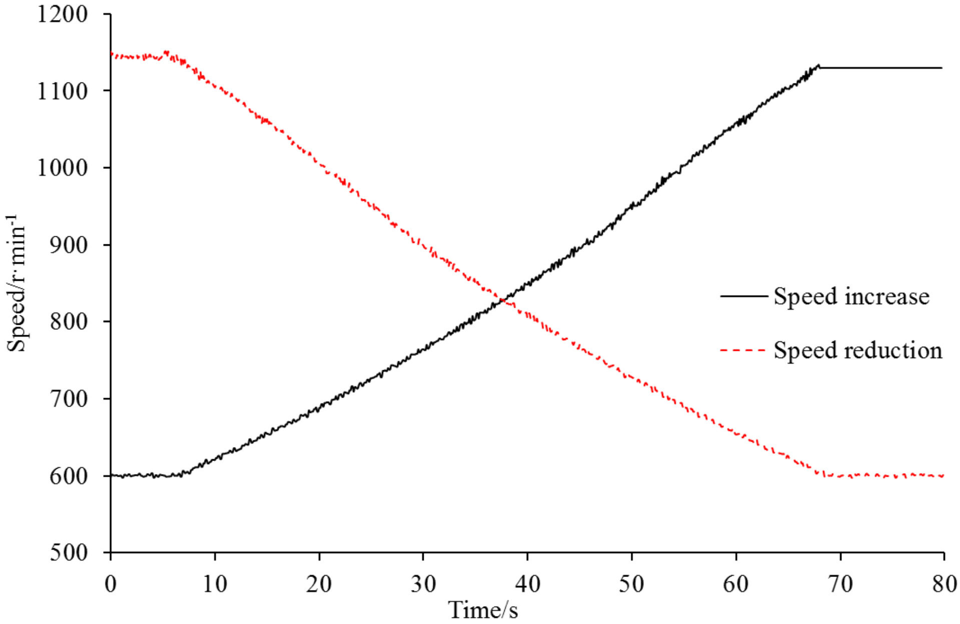


Fig. 3 - Fan speed regulation curve

The adjustable range of the fan speed is tested as shown in figure 4. The adjustable range of the rotating speed of cylinder is 700-1100r/min, the time from the lowest speed to the highest speed is 190.5s, and the average adjusting speed is 2.1r/s. The acceleration curve of the cylinder can be fitted as y=2.06x+683.32, R^2=99.51%, and the deceleration curve of the cylinder can be fitted as y=-2.0823x+1079.8, R^2=99.47%. Compared with the fan speed regulation, the roller speed regulation is slower, mainly because the roller speed regulation belt pulley needs a larger torque. In order to generate enough torque, the chain drive selects a larger transmission ratio, so the regulation speed is slower.

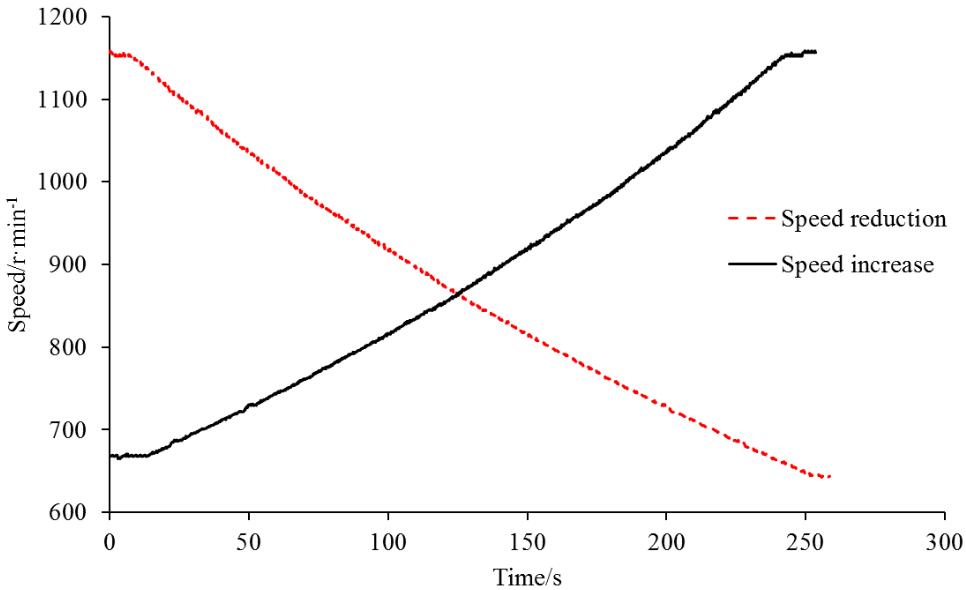


Fig. 4 - Threshing cylinder speed regulation curve

Speed Response Test

During the operation of the fan, the set value of the fan speed is changed, and the speed response curve of the fan is shown in Figure 5. It can be known from the test results that the set value of the fan speed is 745-900-950-850-900r/min. Under the function of speed control system, the actual fan speed changes as follows.

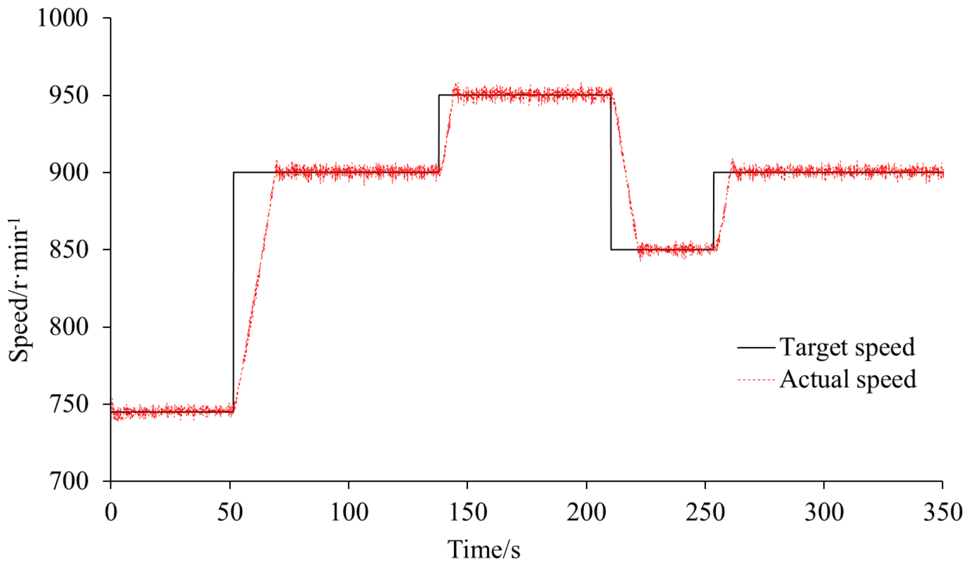


Fig. 5 - Fan speed tracking

When the system is in stable operation, the actual fan speed is shown in Table 2. The average absolute error between the actual speed of the fan and the set speed does not exceed 0.72 r/min, the relative error does not exceed 0.07%, the mean square error does not exceed 2.77 r/min, and the maximum relative deviation is 0.95%.

Table 2

Stabilization phase of cleaning fan

Items	**value**					**Average**
Time period [s]	0～51	69～138	144～210	222～253	261～350	\
Target speed [r/min]	745	900	950	850	900	\
Actual speed [r/min]	745.5	900.8	950.8	850.5	901	\
Absolute error [r/min]	0.5	0.8	0.8	0.5	1	0.72
Relative error [%]	0.06%	0.08	0.08	0.06	0.11	0.07
Mean square deviation [r/min]	2.64	2.97	3.01	2.48	2.73	2.77
Deviation range [r/min]	-6.1～8.8	-8.47～7.7	-8.1～8.5	-7.3～5.9	-7.1～9.1	\
Maximum phase relative deviation [%]	1.2	0.9	0.9	0.7	1.0	0.95

The changes in actual speed during the speed regulation phase are shown in Table 3. The average response time of the fan speed is 1.33 s, the average adjustment time is 6.58 s, the adjustment speed is 11.25 r/s, the overshoot is less than 8 r/s, and the overshoot percentage is less than 0.85%. The fan speed can be adjusted quickly according to the set value.

Table 3

Speed regulation stage of cleaning fan

Items	value				Average
Current speed [r/min]	745	900	950	850	\
Target speed [r/min]	900	950	850	900	\
Response delay [s]	0.9	1.6	1.1	1.7	1.33
Adjustment time [s]	12.2	4	5.2	4.9	6.58
Adjusting speed [r/s]	12.7	12.5	9.6	10.2	11.25
Overshoot [r/min]	7	8.5	7.3	9.1	8.00
Overshoot percentage [%]	0.7	0.8	0.9	1	0.85

During the operation of threshing cylinder, the set value of the threshing cylinder is changed, and the speed response curve of threshing cylinder is shown in Figure 6. It can be known from the test results that the set value of the fan speed is 1000-1050-950-1000 r/min. Under the function of speed control system, the actual fan speed changes as follow.

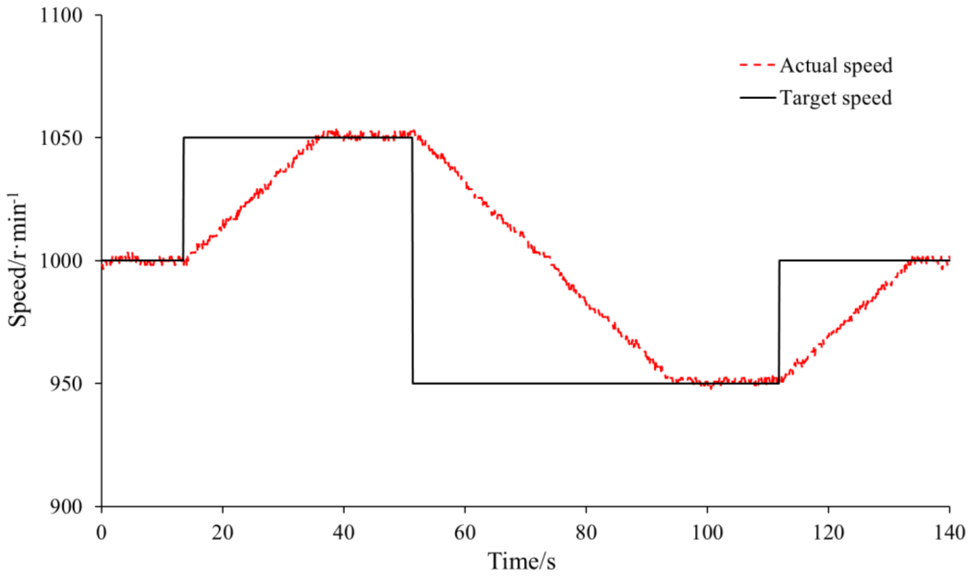


Fig. 6 - Threshing cylinder speed tracking

When the system is in stable operation, the actual threshing cylinder speed is shown in Table 4.The average absolute error between the actual speed of the fan and the set speed does not exceed 0.62 r/min, the relative error does not exceed 0.06%, the mean square error does not exceed 1.15 r/min, and the maximum relative deviation is 0.38%.

Table 4

Stabilization Phase of threshing cylinder

Items	value				Average
Time period [s]	0～13	37～51	95～111	134～160	\
Target speed [r/min]	1000	1050	950	1000	\
Actual speed [r/min]	1000.07	1051.2	951.2	1000	\

Items	value				Average
Absolute error [r/min]	0.07	1.2	1.2	0	0.62
Relative error [%]	0	0.11	0.13	0	0.06
Mean square deviation [r/min]	1.20	1.20	1.05	1.14	1.15
Deviation range [r/min]	-3.2～3.3	-1.1～5.5	-2.2～3.9	-3.3～1.67	\
Maximum phase relative deviation [%]	0.3	0.5	0.4	0.3	0.38

The changes in actual speed during the speed regulation phase are shown in Table 5. The average response time of the fan speed is 1.5 s, the average adjustment time is 27.37 s, the adjustment speed is 12.43 r/s, the overshoot is less than 1.5 r/s, and the overshoot percentage is less than 0.17%.

Table 5

Speed Regulation Stage of threshing cylinder

Items	value			Average
Current speed [r/min]	1000	1050	950	\
Target speed [r/min]	1050	950	1000	\
Response delay [s]	1.2	1.6	1.7	1.50
Adjustment time [s]	21.3	41.3	19.5	27.37
Adjusting speed [r/s]	2.3	2.4	2.6	2.43
Overshoot [r/min]	4.5	\	\	1.50
Overshoot percentage [%]	0.5	\	\	0.17

Variable load test

Set the fan speed to a fixed value and change the engine speed through the throttle to simulate the effect of the load on the speed of the working parts under actual conditions. Set the fan speed to 800r / min; the fan speed when the engine speed is changed is shown in figure 7.

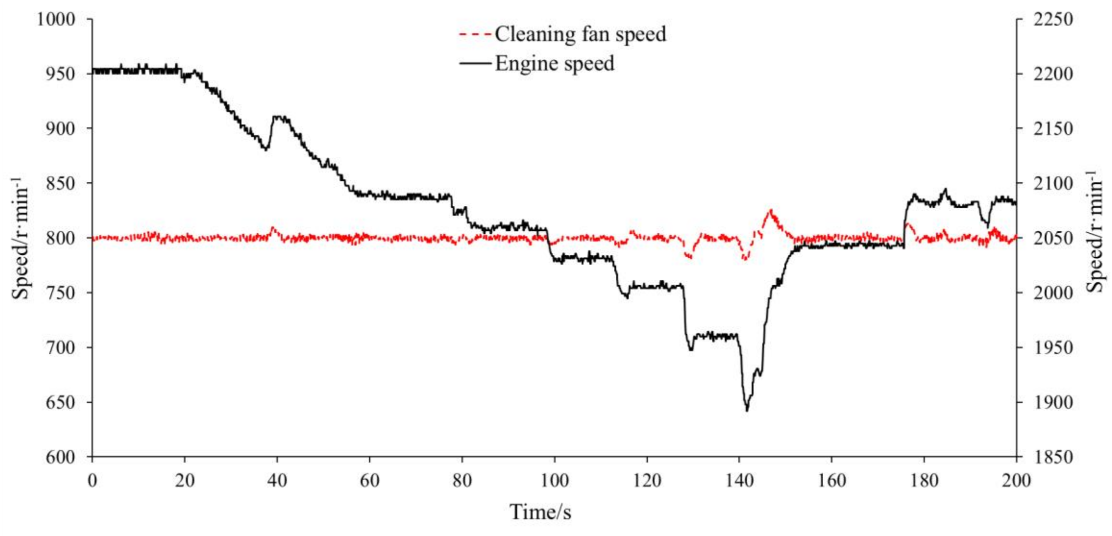


Fig. 7 - Fan speed during sudden load changes

At the initial state, the engine speed is 2200 r/min and the fan speed is 800 r/min. When the engine speed varies from 1890 to 2200 r/min, the average speed of the fan is 800.1 r/min and the mean square deviation is 4.5 r/min. When the engine speed increases suddenly (1890-2040 r/min), the maximum fan speed is 826.1, with a change of no more than 3.3%.When the engine speed drops suddenly (2010-1950 r/min), the minimum fan speed is 787.4 r/min, with a change of no more than 1.6%.The test shows that after adding the engine speed control system, the fan can be stably maintained at the set speed when the input speed changes.

CONCLUSIONS

Aiming at the problem that the rotation speed of the threshing drum and the cleaning fan of the combine harvester cannot be controlled in real time, a stepless speed regulation mechanism for the threshing drum and the cleaning fan speed of the combine harvester is designed and controlled by a stepper motor. The test shows that the adjustable range of the fan speed is 600～1150 r/min, the average adjustment speed is 9.2 r/s, the absolute error of stable speed does not exceed 0.72 r/min, and the maximum relative deviation is 0.95%. The average speed response time is 1.33 s, the overshoot is less than 8 r/s, and the speed change when the engine speed suddenly changes does not exceed 3.3%. The test shows that the adjustable range of the rotation speed of the drum is around 700～1100 r/min, the time from the lowest speed to the highest speed is 190.5 s, and the average adjustment speed is 2.1 r/s. The absolute error of stable speed does not exceed 0.62 r/min, and the maximum relative deviation is 0.38%. The average speed response time is 1.50 s, and the overshoot is less than 1.5 r/s.

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