Electrical Modification and Experimental Study of Combine Harvester Reaping Unit

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Abstract. In order to deal with the gradual shortage of labour force in the aging society, it is necessary to make intelligent and unmanned improvements to mechanical equipment such as combine harvesters for repetitive daily work. Based on a special combine harvester, the electrical modification for its reaping unit is designed, which includes the selection of motor and reducer, the 3D design and finite element analysis for two kinds of working conditions. Moreover, the electrical driver method is proposed, which can automatic adjustment harvest speed based on the walking speed of vehicle. Finally, some filed tests of wheat harvesting verified the correctness for electric refit. The electrical modification of reaping unit provides theoretical basis and experimental data for the robotics research of whole combine harvester.

1. Introduction
Electrification has become the next focus of agricultural machinery research. At present, the existing electric agricultural machinery equipment is electric tractor[1-3]. Independent of diesel engines, electric agricultural machinery has great advantages in efficiency [4-7]. The intelligent control of electric agricultural machinery promotes the full use of its energy.

With the continuous updating of artificial intelligence technology, more and more intelligent unmanned devices have entered our lives. In the future trend, it is necessary to start the intelligent unmanned construction of mechanical equipment such as harvesters that are engaged in repetitive regular work in order to cope with the gradual lack of labour in the aging society.

In the field of agricultural vehicles, the research team at Harper Adams University in Shropshire, UK has developed a series of automatic tractors, automatic combine harvesting[8, 9]. The grain can be planted and sprayed by the farmer in the control room through an automatic tractor, and can be harvested by an automatic combine harvester during the crop harvesting season. The research team believes that over the years, more and more large-scale agricultural machinery has increased the difficulty of precision agricultural production and brought problems such as soil compaction, which will lead to a decline in soil fertility. Their research philosophy is to reduce the degree of soil compaction by introducing automation technology to create a sustainable, multi-sized, light-weight machine.

China Zoomlion Heavy Industry Co., Ltd., cooperated with Jiangsu University have developed an unmanned harvester, which has been launched[10]. This unmanned harvester can realize navigation and operation functions based on path planning. The cutting head and drum control of this model can automatically adjust the working speed, featuring high intelligence, simple operation, flexible working modes, straight driving path and small track deviation.
An DYNAMAX combine harvester developed by Kubota of Japan has an automated unmanned harvesting function that introduces automation technology in teletype control and enables automatic harvesting based on route planning navigation[11]. The future development trends for the combine harvester electrification is unmanned and robotic. Industrial automation technology must be applied to agricultural machinery. Its electrification process will be optimized and the energy consumption will be lower. E-drive technique has obvious advantage in the new agricultural machinery[12-15]. To realize the automation of agricultural machinery and the process of agricultural mechanization, standardization and modularization will also promote the rapid development of electrification, which is bound to provide a new theoretical basis and solutions for the first use of agricultural machinery equipment.

2. Structural Modification for Reaping Unit
Now, we need to carry out oil-to-electricity refit work for one special full-feed combine harvester, and the refit work is concentrated on the reaping unit of the combine harvester. The refit of reaping unit is divided into four parts: eel, cutter bar, PF auger, and conveying chain, as shown in Fig. 1.

![Figure 1. Basic composition of combine harvester reaping unit.](image)

1-Reel; 2-Cutterbar; 3-PF auger; 4-Operation cab; 5-Feed House; 6-tractor; 7-Grain unloading unit; 8-Cleaning fan; 9-Threshing cylinder; 10-Sieve; 11-spread

This section focuses on the structural modifications of one functional components of the conveying chain, which are also called Feed House (FH). The structural modifications for the other three components are similar with FH’s refit.

2.1. Objective of the Electrical Refit for FH
The required input power and rated speed of FH component is 1.4kW and 324rpm, respectively. Original input power is measured through the traditional mechanical transmission. Then, the input axis for FH component should connected with reducer in order to realize electric refit. The technical indicators for FH refit are as follows: 1) selected appropriate motor and reducer; 2) designed 3D model for electric refit; 3) optimized the designed structure by finite element analysis.

2.2. Selection and Structural Design
Based on the power requirement of at least 1.4kw and the speed requirement of at least324 rpm, which are derived from the design indicators of one special combine harvester, the proper power and ratio of motor and reducer can be calculated. Then the selection of motor and its ratio of reducer is determined based on the calculation.

2.2.1. Overall layout and mounting method. The overall layout of FH design can be seen as the left figure of Fig. 2. The reducer will connect the FH input shaft by using some shaft connector. In order to maintain the strength of the welding connector, some reinforcement has been added.
It uses a bracket to connect the motor-reducer combination in order to simplify the mounting plan. And the existing 7 mounting holes on the FH installation frame is used, as shown in the right figure of Fig. 2.

**Figure 2.** Overall layout design and mounting method of FH.

2.2.2. Shaft connection method. The connection between the FH input shaft and motor shaft is based on two shaft keyways, because the transmission torque was too big and larger shock occurred in the actual field operation. Common coupling (e.g. diaphragm coupling and slider coupling, etc) cannot bear the sudden shock from soil or crops. So rigid connection may be the best connection way in the process of electrical modification. As shown in Fig. 3, the two keyways connect the yellow PF shaft with white motor shaft using four M6 bolts.

**Figure 3.** Overall layout design and mounting method of FH.

2.2.3. External dimension comparison. Because the size of motor is outstanding, the original shell can’t handle such situation. The specific extending size can be seen from Fig. 4, which indicates that the extra length of such assembly is about 240mm.

**Figure 4.** Total extending size of FH assembly.

2.3. Finite Element Analysis
When motor works, force put on the connector contains the output torque of motor, the torque generated by motor gravity and its own gravity. All output torque will act on the four through holes, which is indicated in pink arrow along the circle hole. And we add a remote output torque in the position of the motor gravity centre to represent the torque generated by motor gravity. The gravity acceleration and the operation acceleration are signed as red arrows, where the acceleration is 3g. The augmented acceleration -3g means the harvester may have a sudden stop or...
starting, so there will be backward and forward static analysis in the following contents. The force added on the structure is directed in Fig. 5.

**Figure 5.** Loads applied and corresponding stress distribution on FH (when speeding up).

In Fig. 5, the gravity is downward and the speed acceleration is backward. The parameter and result are presented in Tab. 1. The right is Von Mises stress for the FEA analysis (Solidworks 2018) in Fig. 5.

| Condition | Load (N) | Torque (N.m) | Gravity (m/s²) | Inertia (m/s²) |
|-----------|----------|--------------|----------------|---------------|
| Forward   | 300*3    | 73           | 3g             | 3g            |
| Backward  | 300*3    | 73           | 3g             | 3g            |

2.3.1 When speed up
Consider the material of FH bracket is Q235, whose yield stress is 235MPa. So, the corresponding factor of safety, which needs to be close to 10, is about:

\[
\frac{\text{stress}_{\text{yield}}}{\text{stress}_{\text{max}}} = \frac{235 \text{ MPa}}{24.74 \text{ MPa}} = 9.51
\]

Maximum deformation is about: 0.087mm

2.3.2 When speed down
Consider the material of FH bracket is Q235, whose yield stress is 235MPa. So, the corresponding safe coefficient is about:

\[
\frac{\text{stress}_{\text{yield}}}{\text{stress}_{\text{max}}} = \frac{235 \text{ MPa}}{25.61 \text{ MPa}} = 9.18
\]

Maximum displacement is about: 0.091mm

3. Electric Driver Method

3.1. Multi Motor Speed Following Based on PLC
The movement of the main shaft of the engine is transmitted to the moving parts through all levels of mechanical transmission. If the error of mechanical transmission is not considered, the motion of the moving parts can be regarded as linear relationship.

As shown in Fig. 6, suppose in the original mechanical structure, the rotational speed of component a is \( \nu_a \), the rotational speed of component b is \( \nu_b \), if the transmission ratio is \( k_{ab} \), then there is \( \nu_a / \nu_b = k_{ab} \). In the process of harvester movement, the speed of components a and b are all functions of time, which are recorded as \( \nu_a(t) \) and \( \nu_b(t) \), then there is \( \nu_a(t) = k_{ab} * \nu_b(t) \). After adopting the motor mechanism, the rotating shaft speed of each motor is calculated by using the digital encoder. At each sampling time \( k \), the measured speed of component a is \( \nu_a(k) \), and that of component b is
Taking the a part as the benchmark, the speed control error of component a is $e_a = v_a - v_a(k)$, and the tracking error of component b is $e_b = v_b(k) - k_{ab} * v_a(k)$.

The purpose of the control algorithm is to find the control law, so that the control error of component a and the speed following error of component b tend to zero.

3.2. Multi motor Speed Following Based on PLC
As shown in Fig. 7a, the program mode of PLC is circular mode, which completes the following actions in one cycle:
1) To read HMI instructions, write four motor instructions to the current parameters of HMI feedback system and read motor parameters, i.e. communicate with node 1-4 in RS485 communication network.
2) The walking speed of the reader is communicated with node 5 in RS485 communication network.
In action 1, because the communication between PLC and HMI is not open, but sharing variables, HMI and PLC can read and write each other's variables. So, we only need to set the address and so on, and we don't need to design RS485 communication.

Whether the data read and written in each action changes or not, the action is executed in the loop of the main program. Ensure the robustness of the system.

4. Field Test and Discussion
The main objective of the field test for reaping unit is to verify the feasibility of the preliminary electrification design and to collect data to provide reference for the next modification design.
The data that we want to collect in the field test includes the speed and current of each motorized component (e.g. Reel, CB, PF and FH) along with the machine speed.

4.1. Multi Motor Speed Following Based on PLC
The data collect method is shown in Fig. 7b. The current is collected by current sensor and recorded by HMI through PLC. And the speed is collected by the driver and recorded by HMI though PLC.

4.2. Discussion

Figure 8. Collected data for the filed test of reaping unit (include Reel, Cutterbar, PF and FH).

Fig. 8 shows the vehicle speed and corresponding speed and current of four components (only 50 seconds collected data are shown here). And the feasibility of electrification modification of harvester's head was preliminarily verified. The following conclusions and problems were found:
1) Motor selection meets the requirements of operation. The maximum power values of the four motors in the whole harvesting experiment are reel-0.85 kW, cutterbar-1.8 kW, PF Auger-1.2 kW, FH-1.5 kW, respectively.
2) Because the motor can operate at short time and exceed the rated power, and the harvester designs the field. The harvesting gear is M gear, and it is preliminary judged that the selection of motor meets the requirements of operation.
3) In the field experiment, after the harvester opens the throttle and threshing clutch, the car body has high vibration.

5. Conclusion
The electrical modification for reaping unit has finished the electrical driver for harvesting header, and the structural design and electric driver by PLC verify the correctness. Finally, the field test for wheat harvesting confirmed the roboticization for combine harvest has great research prospect.
electrification of the remaining components and field experiments will promote the research on the robotic process of the combine harvester.

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References
[1] Moreda, G.P., M.A. Muñoz-García, and P. Barreiro, High voltage electrification of tractor and agricultural machinery – A review. Energy Conversion and Management, 2016. 115: p. 117-131.
[2] Heidfeld, H., et al. Development of an Electric Powered Light-Stilt-Tractor for the Application of Biological Plant Protection Products in Corn. 2018. Cham: Springer International Publishing.
[3] Babu, R.M., M. S, and N.R. P, Electrical Operated Fan for Cooling System on Agricultural Tractors. 2019, SAE International.
[4] Jackson, J. and J. S. Dvorak, Hybrid Diesel-Electric Drivetrain for Small Agricultural Field Machines. Transactions of the ASABE, 2016. 59(5): p. 1117-1125.
[5] Woopen, T. and S. Hammes, New Battery Driven Vehicle Generation of Electric Tractors. ATZheavy duty worldwide, 2019. 12(4): p. 16-21.
[6] Baek, S.Y., et al., Development of simulation model for electric all-wheel-drive tractor, in 2019 ASABE Annual International Meeting. 2019, ASABE: St. Joseph, MI. p. 1.
[7] Jia, C., W. Qiao, and L. Qu. Modeling and Control of Hybrid Electric Vehicles: A Case Study for Agricultural Tractors. in 2018 IEEE Vehicle Power and Propulsion Conference (VPPC). 2018.
[8] Bautista, A.J. and S.O. Wane. ATLAS Robot:A Teaching Tool for Autonomous Agricultural Mobile Robotics. in 2018 International Conference on Control, Automation and Information Sciences (ICCAIS). 2018.
[9] Bautista, A.J., et al. Development of an Autonomous Hand Tractor Platform for Philippine Agricultural Operations. in 2018 18th International Conference on Control, Automation and Systems (ICCAS). 2018.
[10] Safdar, M.T. and T.v. Gevelt, Catching Up with the ‘Core’: The Nature of the Agricultural Machinery Sector and Challenges for Chinese Manufacturers. The Journal of Development Studies, 2019: p. 1-18.
[11] Li, Q., et al., Effect of supplemental lighting on water transport, photosynthetic carbon gain and water use efficiency in greenhouse tomato. Scientia Horticulturae, 2019. 256: p. 108630.
[12] Pramod, A.S. and T.V. Jithinmon. Development of mobile dual PR arm agricultural robot. in 2nd International Conference on New Frontiers in Engineering, Science and Technology, NFEST 2019, February 18, 2019 - February 22, 2019. Kurukshetra, Haryana, India: Institute of Physics Publishing.
[13] Panchenko, A.V., et al., The automated testing facility based on machine vision for optimizing grain quality control technology. Ninth International Conference on Machine Vision. Vol. 10341. 2017: SPIE.
[14] Sembiring, A., A. Budiman, and Y.D. Lestari. Design and Control of Agricultural Robot for Tomato Plants Treatment and Harvesting, in International Conference on Information and Communication Technology 2017, IconICT 2017, August 25, 2017 - August 26, 2017. Medan, Sumatera Utara, Indonesia: Institute of Physics Publishing.
[15] Gao, G., Y. Zheng, and H. Wang. Kinematic and Static Analysis and Experimental Study for Dual-arm Continuum Robot. in 2019 3rd International Conference on Artificial Intelligence, Automation and Control Technologies, AIACCT 2019, April 25, 2019 - April 27, 2019. Xi'an, China: Institute of Physics Publishing.