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Optimizing Electric Adjustment Mechanism Using the Combination of Multi-body Dynamics and Control

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Abstract

Optimization was carried out on the electric adjustment mechanism for transplanter by using the multidisciplinary design optimization method. According to statics, kinematics, dynamics, and control, disciplinary optimization models were established, with weight, transmission efficiency, vibration frequency, and control error as the optimization goals. Then, a collaborative optimization model for the multidisciplinary design of a mechanism system was constructed. Based on ISIGHT software, the multidisciplinary design integration platform for the electric adjustment mechanism was built. A hybrid algorithm comprising the dual sequential quadratic programming method and the multi-island genetic algorithm was used to calculate the model. Optimization results show that the weight of the electric adjustment mechanism drops by 13.10%, its vibration frequency decreases by 27.71%, its transmission efficiency increases by 20.26%, and the control error decreases by 36.98%. Under the mutual coordination and balance of all discipline goals, the optimal values of the design variables of the electric adjustment mechanism indicate overall optimal performance.

Keywords: collaborative optimization; multi-objective; hybrid algorithm; electric adjustment mechanism; multidisciplinary design optimization

1. Introduction

The electric adjustment mechanism is a key component of adjustable row transplanter. This mechanism is mainly used to adjust the distance between seedling box units and planting arms so as to realize different row spacing for

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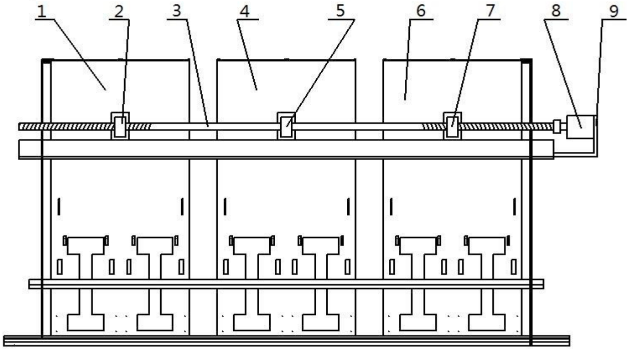
seedling transplanting operation. The electric adjustment mechanism is related to the fields of multi-body dynamics and control. Many complex factors affect the system performance. Moreover, optimization design involves multi-objective, strong coupling, and nonlinear problems[1-3]. The multidisciplinary design optimization (MDO) method takes full account of multiple disciplines and their coupling relationships and makes the overall performance of the system optimal through the coordination of various disciplines [4-5]. The MDO method has been widely used in various fields, including aerospace, automobile, and marine fields [6-9]. The collaborative optimization (CO) method can eliminate the need for extensive systematic analyses in MDO and analyze and optimize all disciplines in parallel [10-13]. Therefore, in this work, we establish a multidisciplinary optimization model of the electric adjustment mechanism for the seedling boxes of high-speed adjustable row transplanter. For this model, the CO method is adopted, and the performance indexes of multi-body dynamics and control are considered as objective functions. The optimization model is optimized by using the combination of the multi-island genetic algorithm and the dual sequential quadratic programming method. The value of the optimized design variable makes the overall performance of the electric adjustment mechanism optimal.

2. Structure and working principle of the electric adjustment mechanism

The electric adjustment mechanism for the seedling box of a high-speed adjustable row transplanter is composed of a positive and negative double helical adjusting shaft, adjusting nut, supporting nut, motor, controller, etc. The horizontal position of the adjustable seedling box unit at both ends of the seedling box can be adjusted. The two adjusting nuts are fixed with two groups of adjustable seedling box units. The supporting nuts and non-adjustable seedling box units are fixed and installed. The adjusting shaft and nuts are installed together. The motor base and motor support are fixed. The motor output shaft is fixed by coupling and by the adjusting shaft (Fig. 1). During the operation of the transplanter, the controller controls the rotation of the motor and drives the rotation of the positive and negative double helical adjusting shaft. The adjustable seedling box unit at both ends moves inside or outside synchronously under the action of the adjusting nut. The adjustable seedling box unit is also fine-tuned under the self-locking action of the silk rod nut so as to prevent it from moving around and interfering with the planting arm during operation.



1,6 Adjustable seedling box unit 2,7 Adjusting screw 3 Adjusting shaft 4 Non-adjustable seedling box unit 5 Supporting screw 8 Motor 9 Motor support

Fig. 1. Schematic diagram of the structure of the electric adjustment mechanism for the seedling box of a high-speed adjustable row transplanter

3. Multidisciplinary design optimization model

3.1. Discipline decomposition

According to the characteristics of the electric adjustment mechanism and the requirements of MDO, the MDO problem of the electric adjustment mechanism is decomposed into multi-body dynamics and control by using the method based on subject analysis (Fig. 2). The design variables, objective functions, and the constraints of each discipline are determined. The design variables are selected and classified according to different system disciplines. Then, a discipline optimization analysis model is established, and a suitable optimization algorithm is determined for each discipline-level optimization.

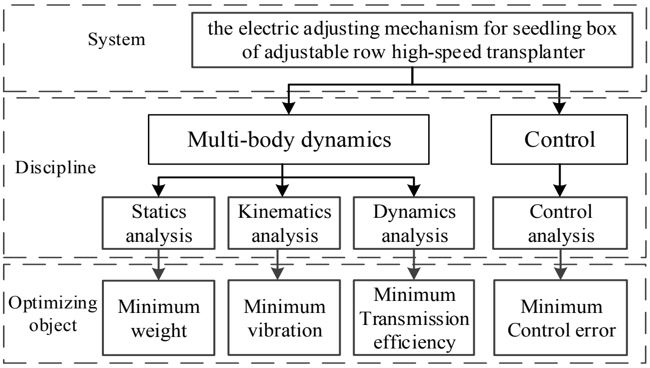


Fig. 2. Disciplinary decomposition of the electric adjustment mechanism of the seedling box of a high-speed adjustable row transplanter

3.2. Subject optimization analysis

3.2.1. Multi-body dynamics analysis

The adjusting shaft is an important component of the electric adjustment mechanism. Its structural stress and strain characteristics affect its working performance directly. By using our relevant knowledge of multi-body dynamics, we analyze the statics, kinematics, and dynamics in this work.

The structural parameters of the electric adjustment mechanism are taken as the design variables, and the weight of the adjusting shaft of the electric adjustment mechanism is taken as the optimization objective. The static optimization of the electric adjustment mechanism is then carried out. The optimization objectives, design variables, and constraints of the electric adjustment mechanism are shown in Table 1.

Table 1. Statics optimization analysis of electric adjustment mechanism

Factor	Parameter	Values
Optimization goal	Weight/kg	Minimum
Design variables	Screw length/mm	[1650, 1850]
	Screw diameter/mm	[16,18]
	Screw thread length/mm	[100, 250]
	Screw thread height/mm	[1.2, 1.5]
	Screw pitch/mm	[1.8, 2.0]
Constraint condition	Screw strength/MPa	$\le [\sigma]$
	Screw stability	≥3
	Screw working length/mm	[100, 200]

In consideration of the structure and working parameters of the adjusting shaft as the design variable and the transmission efficiency as the optimization objective, we perform the kinematics optimization of the electric adjustment mechanism. The kinematics optimization objectives, design variables, and constraints of the electric adjustment mechanism are shown in Table 2.

Table 2. Kinematics optimization analysis of electric adjustment mechanism

Factor	Parameter	Values
Optimization goal	Transmission efficiency	Highest
Design variables	Screw diameter/mm	[16, 18]
	Screw thread height/mm	[1.2, 1.5]
	Screw speed/($r\cdot min^{-1}$)	[0, 1]
	Screw pitch/mm	[1, 3]
Constraint condition	Screw acceleration/($rad\cdot s^{-1}$)	[0, 5]

To avoid any resonance between the electric adjustment mechanism and the seedling box unit, we should perform a structural vibration analysis of the mechanism and ultimately minimize the vibration during operation [14-15]. The axial vibration, torsional vibration, and bending vibration of the mechanism are mainly considered.

We perform the dynamics analysis of the electric adjustment mechanism by taking the structural parameters of the electric adjustment mechanism as the design variable and the minimum vibration of the adjusting shaft of the electric adjustment mechanism as the optimization objective. The dynamics optimization objectives, design variables, and constraints of the electric adjustment mechanism are shown in Table 3.

Table 3. Dynamics optimization analysis of electric adjustment mechanism

Factor	Parameter	Values
Optimization goal	First order vibration frequency/Hz	Minimum
Design variables	Screw diameter/mm	[16,18]
	Screw thread height/mm	[1.2,1.5]
	Screw pitch/mm	[1.8,2.0]
Constraint condition	Shear strength of the dangerous section of the screw/MPa	$\leq [\tau]$
	Bending strength of the dangerous section of the screw/MPa	$\leq [\sigma_b]$

3.2.2. Control optimization analysis

The control precision of the electric adjustment mechanism affects the adjustment of the spacing of the seedling box units directly. The PID control algorithm is used in the system. The PID control factor is taken as the design variable, and the minimum control error is taken as the optimization objective in carrying out the control optimization of the electric adjustment mechanism. The optimization objectives, design variables, and constraints of the control electric adjustment mechanism are shown in Table 4.

Table 4. Control optimization analysis of electric adjustment mechanism

Factor	Parameter	Values
Optimization goal	Control error E	Minimum
Design variables	Proportional coefficient	≥ 0
	Integral coefficient	≥ 0
	Differential coefficient	≥ 0
Constraint condition	Overshoot constraint	≤ 0.2
	System output steady-state constraint/rad	≤ 0.01

3.3. Multidisciplinary design optimization model

The CO method is a widely used two-level optimization method. Its computational structure is similar to that of the existing mechanical and electrical system design in the form of the division of labor. Therefore, the MDO of the electric adjustment mechanism is carried out by using the CO method, and the mathematical model of the MDO of the electric adjustment mechanism is established. The design framework for the multidisciplinary CO of the electric adjustment mechanism is shown in Fig. 3.

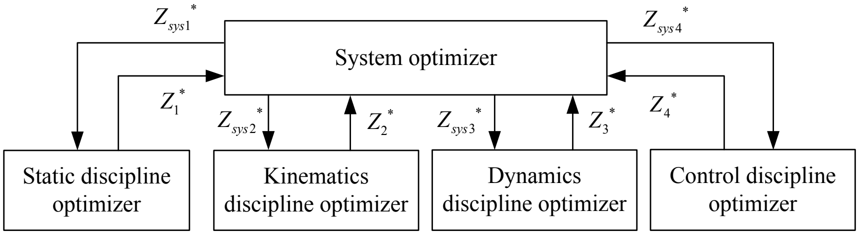


Fig. 3. Multidisciplinary design optimization framework of electric adjustment mechanism

4. Optimization platform construction and result analysis

4.1. Optimization platform construction

ISIGHT software is selected as the integrated platform of the MDO of the electric adjustment mechanism. Considering the serial situation of data flow in the analysis process of each subject software, we use SolidWorks software in geometric modeling and ANSYS/Workbench software in statics and dynamics analysis[3]. Adams software is used in kinematics analysis, and MATLAB/Simulink software is used in control analysis. Integrated software platform for MDO of the high-speed adjustable row transplanter is based on CO.

4.2. Analysis of optimization result

In the MDO of mechanical and electrical systems, the optimization effect of the hybrid algorithm using MIGA and NLPQL is better than that of a single algorithm and other hybrid algorithms [13]. Therefore, based on the CO platform, the combination of MIGA and NLPQL is selected to analyze the optimization of the electric adjustment mechanism. According to the function and work performance requirements of the electric adjustment mechanism, the material of the adjusting screw and nut is Q235, the elastic modulus *E* is 2×1011 Pa, the Poisson ratio is 0.3, the density *ρ* is 7860 kg·m^{-3}, and the friction coefficient of the screw pair is 0.15. The row spacing is adjusted from 200 mm to 300 mm, and the total weight of the seedling box and seedling carrier is 33.6 kg. The optimization results for the system optimization objectives and design variables are shown in Table 5.

Table 5. Optimization results of electric adjustment mechanism

Model elements	Optimal parameters	Initial values	First step optimization with MIGA		Second step optimization with NLPQ		Total increment /%
			Optimization results	Relative increment/%	Optimization results	Relative increment/%	
Objectives	Weight/kg	2.633	2.346	-10.90	2.288	-2.47	-13.10
	Transfer efficiency/%	35.10	40.07	14.16	42.21	5.34	20.26
	First-order vibration mode/Hz	257.83	192.44	-25.36	186.38	-3.15	-27.71
	Control error/E	0.530	0.429	-19.06	0.334	-22.14	-36.98
Variables	Screw length/mm	1850	1841.63	-0.45%	1833.11	-0.46%	-0.91%
	Screw thread length/mm	150	140.4	-6.40%	133.77	-4.72%	-10.82%
	Screw diameter/mm	18	17.11	-4.94%	16.26	-4.97%	-9.67%
	Screw thread height/mm	1.5	1.388	-7.47%	1.365	-1.66%	-9.00%
	Screw pitch/mm	2	1.945	-2.75%	1.916	-1.49%	-4.20%
	Screw speed/(rad·s^{-1})	0.9	0.888	-1.33%	0.878	-1.13%	-2.44%
	Proportional coefficient	5	4.41	-11.80%	4.17	-5.44%	-16.60%
	Integral coefficient	10	12.75	27.50%	14.93	17.10%	49.30%
	Differential coefficient	5	2.32	-0.536	0.96	-58.62%	-80.80%

According to the analysis of Table 5, under the premise of satisfying stiffness and strength, the total weight of the ECM is reduced from 2.633 kg before optimization to 2.228 kg, representing a reduction of 13.1%. This condition makes the whole structure compact and reduces the manufacturing cost. The transmission efficiency increases from 35.1% to 42.1%, representing an increase of 20.26%, reduces the working resistance, and minimizes the regulating energy consumption. The first-order vibration frequency is optimized from the initial state of 257.83 Hz to 186.38 Hz, representing a reduction of 27.71%. The force is distributed evenly, and the fluctuation is minimal. As a result, the mechanism becomes stable and reliable. The control error is optimized from 0.530 to 0.334, representing a reduction of 36.98%. The reliability and stability of the regulation is also enhanced. As indicated by the analysis of Fig. 6, the optimization effect of the combinatorial optimization algorithm on the design variables of the electric control regulation mechanism is obvious under the premise of satisfying the actual working state constraint condition. The MIGA algorithm searches for the optimal value interval in the constraint range of the design variable globally and then optimizes the optimal value in the optimal value interval through the NLPQL algorithm. The MIGA algorithm finally makes each design variable weigh the constraints in the different disciplines of the system. The optimal design value is obtained to satisfy the global optimum of the system.

4.3. Test verification

According to the variable value of CO, the electric adjustment mechanism of the seedling box of the high-speed rice transplanter is developed, and an indoor performance test is carried out. When the row spacing is adjusted from 200 mm to 300 mm and the total weight of the seedling box and seedling carrier is 33.6 kg, the weight of the adjusting shaft is 2.418 kg, the transmission efficiency is 40.29, the first-order vibration frequency is 195.47 Hz, the control error is 0.357, and the relative error of the optimized value is less than 5%. This outcome shows that the optimization result is reliable. The stability of the adjusting shaft is 4.5, the acceleration of the adjusting screw is 2.4 rad/s, the overshoot of the control system is 0.12, and the steady state of the system output is 0.007 rad. These conditions meet the design requirements.

5. Conclusion

The electric adjustment mechanism are divided into multi-body dynamics and control. The mathematical MDO model of the electric adjustment mechanism based on the CO method is established. Based on ISIGHT software, the integrated platform of the electronic adjustment is established on the basis of the CO framework. The optimization results are obtained by using the hybrid optimization algorithm. The weight of the control system is reduced from 2.633 kg to 2.288 kg, representing a reduction of 13.1%. The first-order vibration frequency is optimized from 257.83 Hz to 186.38 Hz, representing a decrease of 27.71%. The transmission efficiency is increased from 35.1% to 42.21%, denoting an increase of 20.26%. The error of the control system is reduced from 0.53 to 0.343, representing a reduction of 36.98%. The four optimization objectives are all satisfactory. As a result, under the coordination and tradeoff among the optimization objectives of various disciplines, the optimization of all the design variables obtained makes the overall working performance of the electric adjustment regulator optimal.

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