

Practical Approaches for the Design of an Agricultural Machine

Zhiying Zhu and Toshio Eisaka

Abstract—The precision agriculture has been progressing rapidly to improve the efficiency of operation with the quality and consistency of products. Intelligent machines with high-tech sensors have been developed exploiting information technology and getting widely used. On most of farms, however, there still works simple inexpensive agricultural machines. From cost saving and sustainable development point of view, utilization of existing facilities can be significant alternative strategy. In this paper, we propose two design methods to improve an existing agricultural machine. One is modifying relevant structural parameters of the existing machine by numerical optimization. The other is appending an actuator and a controller to a machine and then employing simultaneous optimization of both controller and machine parameters. We also compared their performance and robustness.

Keywords—Agricultural Machine, Genetic Algorithm, Hybrid automaton, Simultaneous Optimization.

I. INTRODUCTION

COMPUTER technology, automation and robotics have been widely used in the field of agriculture. These information-based strategies, the so-called “precision agriculture” is promising paradigm to improve the efficiency of operation with the quality and consistency of products under uncertainty of the environment [1]-[4].

Productivity is increased in sustainable agricultural initiative because of mechanism design and control of its dynamics. Much research has been done for designing new machine structures and various active control strategies, respectively [5]-[12]. In Japan, sophisticated methodologies such as GPS locators and intelligent robotics have been applied to the farm machines [13]-[14]. However, the productivity in Japan cannot be improved in the same way as in the Western countries because of the differences of weather condition, land condition and limited of farm area. Instead of extended high-tech machines, small-sized tunable machines can be a better solution in such environment. Moreover, on most of farms, there still works simple inexpensive agricultural machines. From cost saving and sustainable development point of view, utilization of existing facilities can be significant alternative strategy.

Manuscript submitted June 24, 2009.

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In this paper, we propose two design methods to improve an existing agricultural machine: a sugar beet toppler. In both approaches, first, we introduce a basic structure of an existing beet toppler and derive a hybrid nonlinear model of it with adjustable structural parameters. Based on the model, the first approach is to obtain the adequate value of the adjustable structural parameters by numerical optimization without altering the basic structure of the existing toppler. The second approach is appending an actuator and a controller to a toppler, then, employs simultaneous optimization of both controller and machine.

In the second approach, the toppler is a structure-control combined system. Integrated design of structure-control combined system enhances overall performance [15]-[18]. As the authors' knowledge, however, structure/control simultaneous optimization for nonlinear agricultural machines has not been treated.

We conclude this paper noting that the performance of the toppler can be heightened by two proposed approaches, and solutions are found out to maintain accurate operation in high speed running situation.

The paper is organized as follows. In Section 2, kinematics of an existing beet toppler is introduced and a nonlinear dynamic model of it with adjustable structural parameters is derived. While in Section 3, proposed two approaches to design the toppler system are described, and relevant best parameter unit is obtained. In Section 4, performances of two approaches are compared and robustness is also discussed. Section 5 is a conclusion.

II. MODELING OF A SUGAR BEET TOPPLER

A sugar beet toppler, driven by a tractor, is a pre-harvest machine that cut off leaves from beet crops. The basic view of the sugar beet toppler is displayed in Fig.1. The toppler is simply composed of the conrod and the flywheel. The flywheel is introduced to press the beet and cut off leaves of the beet with an equipped knife at the bottom. The conrod is applied to suspend the flywheel and fit it around the bumpy ground. Usually, running speed of a toppler is slower than that of a harvester. In a farm, topplers run around at the speed of 4km/h, and the topplers can cut off leaves successfully. However, if the topplers run faster to cater for the harvesters, the flywheel will jump and fail to cutoff the leaves. In what follows, we deduce a mathematical model of the beet toppler. First, kinematics of the beet toppler is described and then dynamics of it is considered [19].

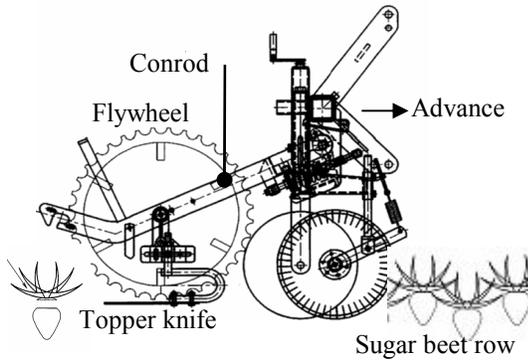


Fig.1 Schematic view of a sugar beet topper

A. Kinematics of the beet topper

Based on Fig.1, we can obtain a simplified structural model of beet topper composed of the conrod and the flywheel, as shown in Fig.2.

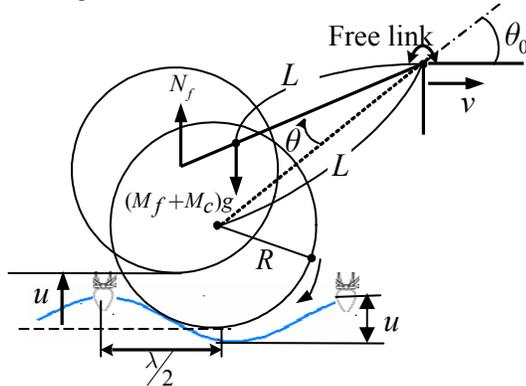


Fig.2 Simplified structural model of beet topper unit

Here, the mechanism of free link part with a spring and a dashpot is illustrated in Fig.3. Symbols mentioned in Fig.2 and Fig.3 are defined in Table I.

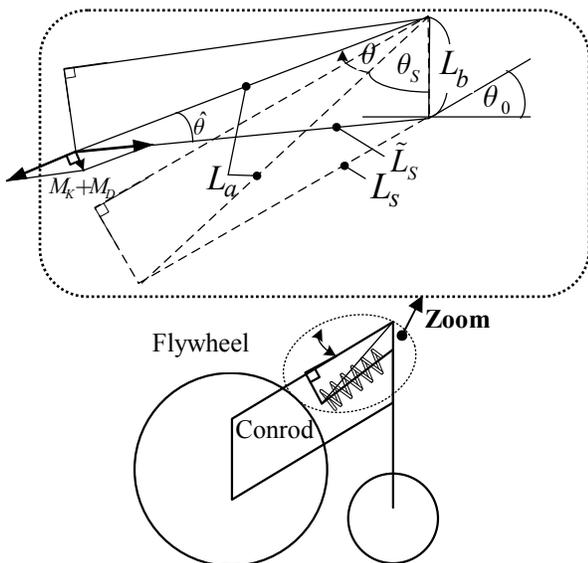


Fig.3 The mechanism of free link with spring and dashpot

TABLE I SYMBOL OF A BEET TOPPER UNIT

Symbol (unit)	Substance
M_f (K g)	weight of wheel
R (m)	radius of wheel
M_c (K g)	weight of conrod
L (m)	length of conrod
L_G (m)	length of center of gravity
I_U (K g · m ²)	moment of the unit
θ_0 (rad)	nominal angle of conrod
θ (rad)	actual angle of conrod
u (m)	height of the bottom of wheel
u_0 (m)	vertical interval of the ground
v (m/s)	velocity of unit
N_f (N)	normal force
λ (m)	wavelength of beet row
K (N/m)	spring coefficient
M_k (Nm)	moment caused by spring
D (N/m/s)	dashpot coefficient
M_D (Nm)	moment caused by dashpot
L_s (m)	natural length of spring
\tilde{L}_s (m)	varied length of spring
L_a, L_b (m)	lengths of link

Actual angle of conrod: $\theta(t)$ is uniquely derived from the geometrical relationship of the height of the wheel: $u(t)$ as,

$$u(t) = 2L \sin \frac{\theta(t)}{2} \cos(\theta_0 - \frac{\theta(t)}{2}) \tag{1}$$

Within small θ , because of $\sin \theta \cong \theta, \cos \theta \cong 1$, (1) can be approximated as,

$$u(t) \cong L\theta(t) (\cos \theta_0 + \frac{\theta(t)}{2} \sin \theta_0). \tag{2}$$

Consequently we obtain static input: $u(t)$ -output: $\theta(t)$ model of the unit as,

$$\theta(t) \cong -\frac{1}{\tan \theta_0} + \sqrt{\left(\frac{1}{\tan \theta_0}\right)^2 + \frac{2u(t)}{L \sin \theta_0}} \tag{3}$$

B. Dynamics of the beet topper

Dynamics of a beet topper can be described in two different situations: a ground mode or a jumping mode. In each mode, a topper has each differential equation, and they are switched each other by certain conditions. Consequently, a hybrid automaton is derived as a total model of a beet topper (see Fig. 4) [20].

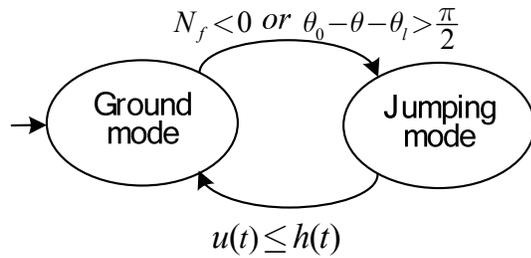


Fig. 4 Hybrid automaton describes dynamics of the topper

Next, differential equations on angle of conrod: $\theta(t)$ of each mode and switching conditions of each other are deduced.

B-1 Ground mode model

When the topper unit is on the ground, with the differentiation of (3), dynamical equation of the topper unit is described as,

$$\ddot{\theta} \simeq \frac{\ddot{u} - L\dot{\theta}^2 \sin \theta_0}{L(\theta \sin \theta_0 + \cos \theta_0)}, \quad (4)$$

$$\text{where, } \dot{\theta} \simeq \frac{\dot{u}}{L(\theta \sin \theta_0 + \cos \theta_0)}. \quad (5)$$

In this mode, the normal force N_f caused by the ground is expressed as,

$$N_f = \frac{I_u \ddot{\theta} + (M_f + M_c)g L_G \cos(\theta_0 - \theta) + M_K + M_D}{\cos(\theta_0 - \theta) \sqrt{L^2 + R^2 + 2LR \sin(\theta_0 - \theta)}} \quad (6)$$

where, the moment caused by the spring and the dashpot is calculated by,

$$M_K + M_D = L_a \left\{ K(\tilde{L}_s - L_s) + D \frac{d\tilde{L}_s}{dt} \right\} \sin \hat{\theta} \quad (7)$$

Here, \tilde{L}_s , L_s and $\sin \hat{\theta}$ as shown in Fig.3 are expressed with length of link L_a , L_b and related nominal angle θ_s as follows using cosine theorem.

$$\tilde{L}_s^2 = L_a^2 + L_b^2 - 2L_a L_b (\cos \theta \cos \theta_s - \sin \theta \sin \theta_s) \quad (8)$$

$$L_s^2 = L_a^2 + L_b^2 - 2L_a L_b \cos \theta_s \quad (9)$$

$$\sin \hat{\theta} = \sqrt{1 - \cos^2 \hat{\theta}} = \sqrt{1 - \left\{ \frac{L_a^2 + \tilde{L}_s^2 - L_b^2}{2L_a \tilde{L}_s} \right\}^2} \quad (10)$$

It should be noted that the normal force: N_f is always positive in the ground mode.

B-2 Jumping mode model

When the wheel is jumping, the conrod torque is yield by force of gravity and the moment caused by the spring and the dashpot. Thus, the unit is subjected to the next differential equation.

$$I_U \ddot{\theta} = -(M_f + M_c)g L_G \cos(\theta_0 - \theta) - (M_K + M_D) \quad (11)$$

Here, $M_K + M_D$ can also be deduced by (7),

B-3 Switching conditions

Switching conditions from ground mode to jumping mode or the opposite are derived respectively as follows.

B-3-1 From ground mode to jumping mode:

The beet topper unit on the ground will leave the ground when the normal force becomes negative or if the wheel slips down due to steep slope. Namely, the condition is described as,

$$N_f < 0 \quad \text{or} \quad \theta_0 - \theta - \theta_i > \frac{\pi}{2} \quad (12)$$

where, θ_i denotes slope angle of the soil.

B-3-2 From jumping mode to ground mode:

The beet topper unit in the air will touch down again if the height of the wheel bottom from the nominal height: $u(t)$ becomes less than or equal to that of the soil (or beet): $h(t)$. The condition can be expressed as,

$$u(t) \leq h(t) \quad (13)$$

In order to complete high-accuracy even if in high speed running, it is necessary to keep the topper unit in the ground mode. In other words, the normal force should be positive at any time. In the following section, passive and/or active ways to solve this problem will be proposed.

III. DESIGN APPROACHES

In this section we introduce two approaches to realize high performance integrated topper system. The first approach is to tune adjustable topper unit parameters by biosystem-inspired optimization algorithm. The second approach employs simultaneous optimization both of a controller and a machine.

In both approaches, the following situations are assumed.

1. The ground with sugar beet rows is assumed to be sinusoidal variation, and beets are planted at wave tops.
2. The ground is neither elastic nor stiff.
3. Velocity of the unit is constant.

Assumption 1 provides the height of the bottom of wheel: $u(t)$ at the ground mode as the following,

$$u(t) = -u_0 \sin \omega t; \quad \omega = \frac{2\pi}{\lambda} v. \quad (14)$$

The goal of the design is to maintain the normal force: N_f as to be around 300(N) to hold down the beets adequately and to keep the machine in ground mode, when the topper's running speed is around 8km/h which is double speed as compared to present situation.

A. Design Approach 1

In the first approach, we optimize the tunable topper unit parameters $[K, R, \theta_0, D, L, M_c, M_f]$ by genetic algorithms without altering the basic scheme of the existing topper shown in Fig.2

and Fig.3 [21]-[24]. This approach utilizes the existing facilities and also does not include active device, then it is economical and sustainable solution.

To achieve the goal, firstly we define the evaluate index as,

$$J = \int_0^{0.5} (|N_f(t) - 300| + P) dt, \quad (15)$$

where, P is the penalty to avoid vibrating motion and decided as,

$$N_f(k) - N_f(k-1) \begin{cases} \geq 2.5, \text{ then } P = 10000 \\ < 2.5, \text{ then } P = 0 \end{cases} \quad (16)$$

Here, k is every 1[ms] sampling.

The normal force N_f is calculated by (6) with (3), (4), (5) and (14) substituting $v=8$ in the ground mode, and N_f is fixed to be 0 in the jumping mode.

To obtain reality-based solution, the following physical constrains and also bounds constrains are imposed.

$$R + 0.3 \leq L \leq 0.02 \cdot M_c, R \leq 0.01 \cdot M_f \quad (17)$$

$$[1, 0.1, 0.1, 0, 0.1, 1, 1] \leq [K, R, \theta_0, D, L, M_c, M_f] \leq [10^7, 1, 1.57, 1000, 2, 100, 100] \quad (18)$$

The parameters L_a , L_b and L_s are fixed as $L_a = 0.276[m]$, $L_b = 0.10[m]$, $L_s = 0.223[m]$ which are used in an existing topper.

The Matlab™ GA tool box was employed to decide optimal parameters. In GA Toolbox, options were selected as shown in Table II.

TABLE II OPTIONS OF GA

Option	Substance
Genes	Tuning parameters $[K, R, \theta_0, D, L, M_c, M_f]$
Range	Inequality (18)
Population type	Double vector
Population size	200
Selection function	Stochastic uniform
Mutation	Gaussian, Scale: 1.0, Shrink: 1.0
Crossover	Scattered

A plot of the best values of the fitness function (evaluate index) at each generation is demonstrated in Fig.5. From Fig.5, we notice that over successive generations, the population “evolves” toward an optimal solution. Best evaluate index was 22887. Relevant optimal parameters are

$$[K, R, \theta_0, D, L, M_c, M_f] = [6.3 \times 10^5, 0.1, 0.1, 1.9, 0.46, 27., 10.8].$$

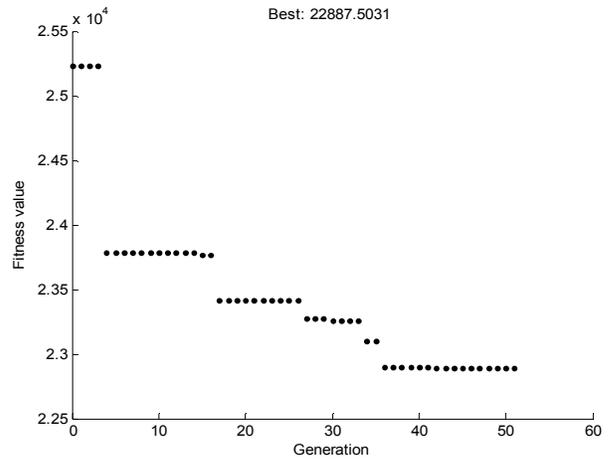


Fig.5 Improvement of fitness for Approach 1.

B. Design Approach 2

In the second approach, to improve performance, an actuator (electric motor) and a PID controller are added to the topper unit, then, employs simultaneous optimization algorithm to both controller and machine parameters [25]. The reference value of normal force and the running speed of the topper are the same as those of Approach 1.

The basic framework of the control system is shown in Fig.6.

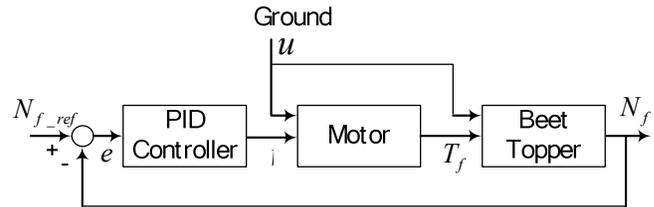


Fig.6 Framework of beet topper control system.

Here, the motor is equipped at the fee link shown in Fig. 2. The N_{f_ref} is reference value of normal force, V is input voltage to the motor and T_f is output torque of the motor that “helps” to keep output of the beet topper unit around 300[N] eliminating the disturbance from the ground.

Additional symbols including a PID controller and a motor are displayed in Table III.

TABLE III ADDITIONAL SYMBOL OF AN ACTIVE BEET TOPPER UNIT

Symbol (unit)	Substance
$K_m(Nm/A)$	motor torque constant
K_g	gear ratio
$R_m(\Omega)$	armature resistance
K_p, K_I, K_D	PID coefficients
$T_f(Nm)$	motor’s output torque
$V(V)$	input voltage to the motor

We then optimize the tunable extended active topper parameter unit $[K_p, K_i, K_d, K_m, K_g, R_m, K, R, \theta_0, D, L, M_c, M_f]$ by genetic algorithms.

The evaluate index (15),(16), physical and bounds constrains (17),(18), are adapted again. However, the normal force N_f in the ground mode caused by the ground and controller-motor is changed from (6) to the following,

$$N_f(t) = \frac{I_u \ddot{\theta} + (M_f + M_c)gL_G \cos(\theta_0 - \theta) + M_K + M_D + T_f}{\cos(\theta_0 - \theta)\sqrt{L^2 + R^2 + 2LR \sin(\theta_0 - \theta)}} \quad (19)$$

Here, the T_f produced by the motor is given as,

$$T_f(t) = \frac{K_m(V(t) - K_m K_g \dot{\theta}(t))}{R_m} \quad (20)$$

and,

$$V(t) = K_p e(t) + K_i \int_0^t e(\tau) dt + K_d \frac{de(t)}{dt} \quad (21)$$

Also, the next bound constrains for the additional parameters is considered.

$$[0, 0, 0, 0, 0, 0] \leq [K_p, K_i, K_d, K_m, K_g, R_m] \leq [20, 20, 20, 1000, 1000, 1000] \quad (22)$$

Moreover, considering on feasibility of the machinery, V is limited to $[-10, 10]$.

The Matlab™ GA tool box was employed to decide optimal parameters. The same GA options shown in Table II were used. A plot of the best values of the fitness function (evaluate index) at each generation is demonstrated in Fig.7.

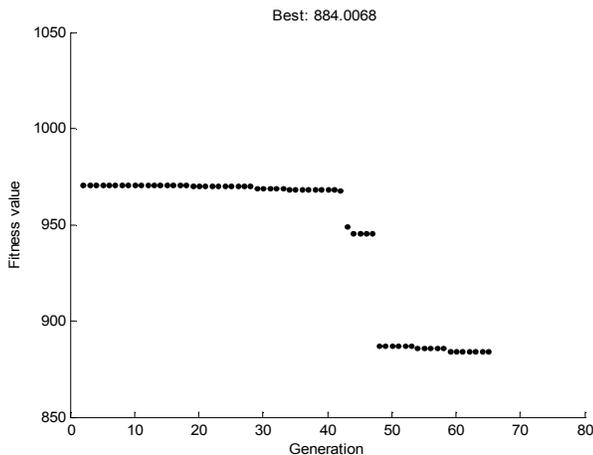
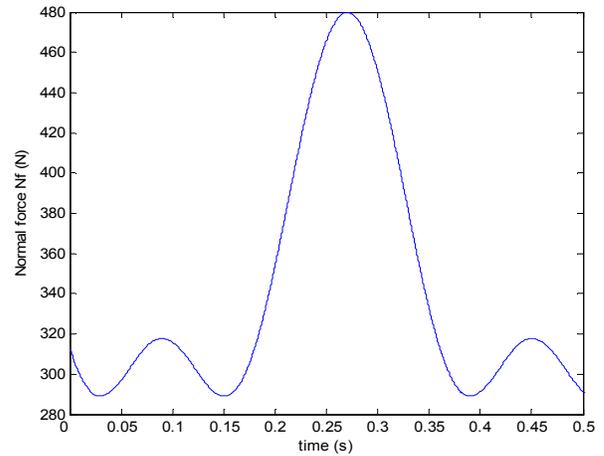


Fig.7. Improvement of fitness for Approach 2.

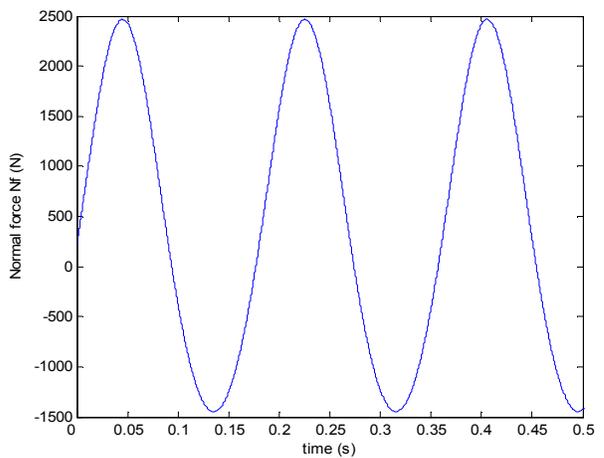
Best evaluate index was 884. Relevant optimal parameters are $[K_p, K_i, K_d, K_m, K_g, R_m, K, R, \theta_0, D, L, M_c, M_f] = [0.0011, 0.023, 0.00016, 21.7, 0.0040, 0.90, 5.0 \times 10^5, 0.1, 0.105, 0.44, 0.4, 22, 13.8]$.

IV. EVALUATION

In this section, we will evaluate these two approaches compared to an existing topper. First of all, the performance of an existing commercial topper is illustrated below.



(a)



(b)

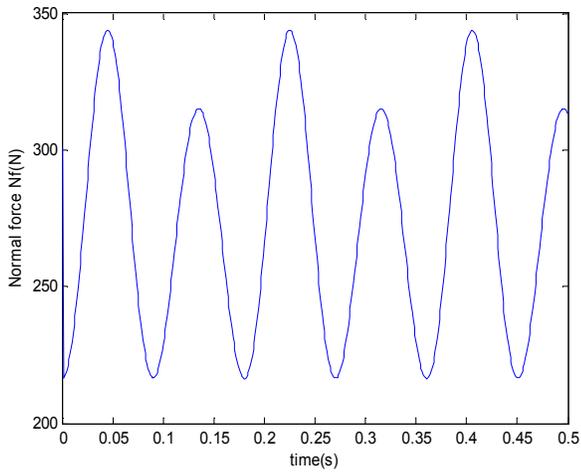
Fig. 8 Natural force of existing topper
(a) running speed is 4km/h
(b) running speed is 8km/h

Figure 8 shows that we cannot satisfactorily speed up existing machine on present form, because if it runs in 8km/h, the flywheel will jump and fail to cutoff the leaves or damage the beet crops with strong pressure.

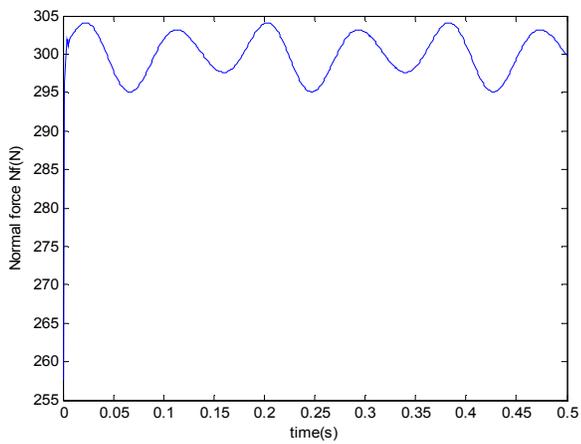
Figure 9 illustrates performance of proposed design in high-speed running. Both toppers show better performance than low-speed existing topper, comparing Fig 8(a) with Fig.9.

Figure 10 and Fig. 11 are input and output of the motor designed by approach 2. The results show that the motor assists the motion of the topper adequately with reasonable electric resource.

We see that existing parameters fail to stay at ground mode with high speed running. On the contrary, proposed topper will be expected to satisfy design goal.



(a)



(b)

Fig.9 Natural force of proposed toppers with running speed: 8km/h
(a) designed by approach 1, (b) designed by approach 2.

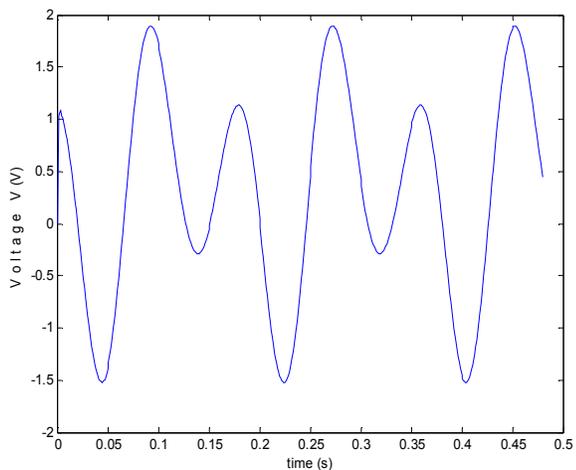


Fig.10. Input to the motor

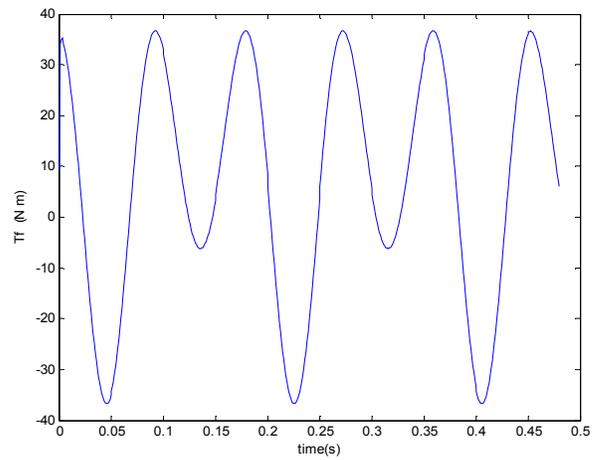
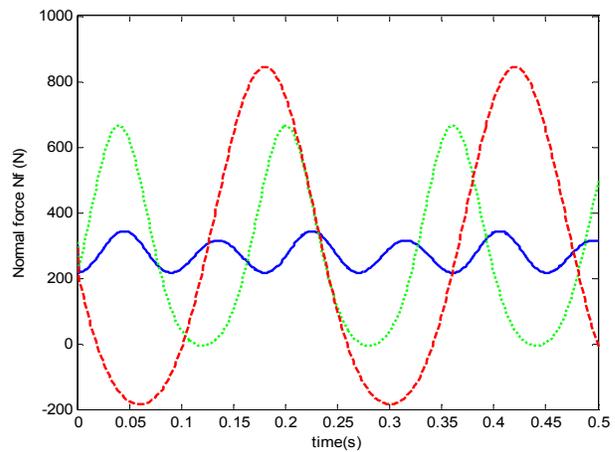


Fig.11. Output of the motor

In the practical point of view, however, the running speed will change and the mathematical model has some uncertainties. The robustness is checked in Fig. 12 and Fig.13. These figures show the history of natural force of the proposed topper with several running speeds and parameter changes. Both figures indicates that the topper given by approach 2 still stay in ground mode in all situations, oppositely, the topper given by approach 1 does not.

Consequently, if we have precise model and we can maintain the speed of the tractor, then, approach 1 is a good low-cost solution. If not, however, we should consider approach 2 to satisfy the specifications.



(a)

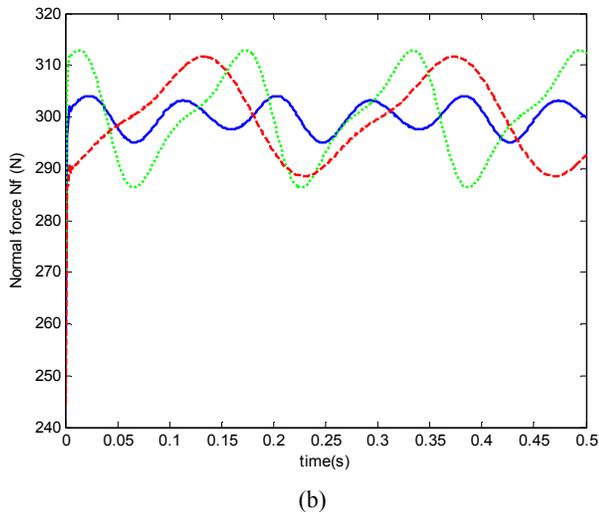
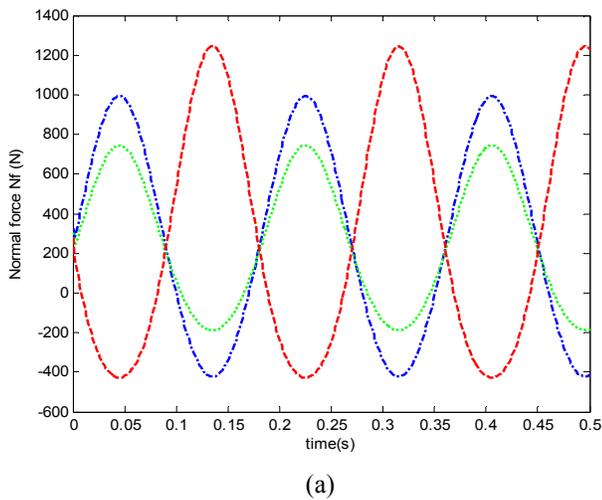
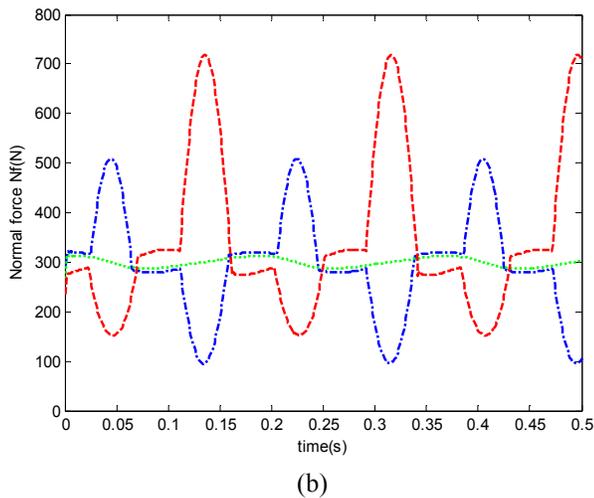


Fig.12 Natural force of proposed toppers with several running speed
dash: 6km/h, solid: 8km/h, dot: 9km/h
(a)Approach 1, (b) Approach 2



(a)



(b)

Fig.13 Natural force of proposed toppers with change of parameters
dash: +5%, solid: -5%, dot: random
(a)Approach 1, (b) Approach 2

Lastly, the result of each topper is summarized in Table IV.

TABLE IV PARAMETER RESULTS OF EACH TOPPER UNIT

Symbol	Existing	Approach 1	Approach 2
K	7.2×10^5	6.3×10^5	5.0×10^5
R	0.32	0.1	0.1
θ_0	0.42	0.1	0.1
D	0	1.9	0.44
L	0.62	0.46	0.40
M_C	30	27	22
M_f	30	10.8	13.8
K_p, K_I, K_D	NA	NA	$1.1 \times 10^{-3}, 0.023, 1.6 \times 10^{-4}$
K_m	NA	NA	21.7
K_g	NA	NA	0.004
R_m	NA	NA	0.9

Compared to existing topper, smaller wheel with shorter conrod will have better performance in both approaches. The kinematic parameters have not so much difference with or without controller.

V. CONCLUSION

In this paper, redesign strategies of a sugar beet topper machine to improve efficiency of harvest have been presented. First, a mathematical model of a topper has been derived. Then, based on the model, two redesign approaches have been proposed and evaluated by computer simulations. The first approach is to obtain the adequate value of the adjustable structural parameters by numerical optimization without altering the basic structure of the existing topper. The second approach is appending an actuator and a controller to a topper, then, employs simultaneous optimization of both controller and machine. Both results satisfy the design specification, the first solution is easy and inexpensive way, on the other hand, the second solution have better performance with good robustness.

These model based design strategies can be applied to general farm machines.

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