A NOVEL 2-D FUZZY CONTROLLER FOR HARVESTER HEAD CUTTING OPERATION BASED ON KINEMATIC ANALYSIS

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Cutting operation always determines the efficiency of the harvester. In order to make the cutting operation efficient, a novel 2-D fuzzy control strategy is applied to the control system. Kinematic models during the cutting process was built. Simulation models of chain saw hydraulic system and control strategy are established based on AMESim and Matlab/Simulink. The result of simulation proves that with the novel closed-loop fuzzy control strategy, 0.25 second is saved during the harvester cutting process(about 18 seconds), the cutting efficiency increased by 1.4%, and energy consumption decreased by 4.5%. The new control strategy can make the cutting operation better than before.

Keywords: Harvester head, Cutting operation, Fuzzy control, Feeding rate

1. Introduction

With the global increased demand of timber, many kinds of forest equipment have been developed. Harvester which was invented in 1960s are commonly used in forest operations today [1]. It is equipped with a high efficient actuator called harvester head [2]. Harvester head can perform the following actions: timber cutting, timber falling and timber feeding. The chain saw cutting system which is applied to the timber cutting program plays an important role in the harvester head. References showed that the saw motor, pumps and the power transmission line in the cutting system may cause much power consumption. Nowadays a lot of researches and experience of the timber cutting are conducted and all the methods are to get a good cutting performance and better efficiency [3]

As can be seen in fig.1 b), the saw chain system is located at the bottom of the harvester head, and it is composed of hydraulic motor, feed cylinder, saw bar and

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saw chain. The saw chain is driven by the hydraulic motor, and the feed cylinder is applied to provide feeding force of the saw bar. Fig.2 shows timber cutting operation of the harvester head. Generally speaking, the cutting process lasts less than one second. In order to be more efficient, the cutting process should be as soon as possible. Cutting time is directly determined by the speed of feeding cylinder, but the feeding speed can’t be increased endlessly. The higher speed leads the faster cutting to a peak, furthermore, beyond this peak, the cutting speed decreases sharply. So it is important to control the speed of the feeding cylinder to get a quicker cutting process.

a）harvester head b）saw chain cutting system

Fig.1 Saw chain cutting system on the harvester head

Fig.2 Timber cutting operation of the harvester head

In the last few years the applications of fuzzy logic techniques have been used in the control system. Fuzzy logic is arisen from the desire of linguistic description for complex systems and it can translate the human experience to automatic control strategies [4-5]. With the development of the fuzzy logic, many kinds of fuzzy control strategies have been developed, such as 2-D fuzzy and T-S fuzzy [6-7]. Most fuzzy control products are rule-based systems. Fuzzy logic can apply for vehicle steering system, servo injection control system[8-10], Variable flow valve control system [11] , machinery transmission hydraulic system[12,13], elevator energy saving[14] and wind energy conversion system[15]. Now a dedicated fuzzy inference system was introduced in training of human operators of harvester [16], but the control method of the harvester cutting is still in an old manner. And no special method is applied to control the feed cylinder when the harvester head is cutting the timber. The aim of this paper is to produce a novel controller for the timber cutting.

2. Kinematic model of cutting operation

Sawing and feeding are two separate motions in the timber cutting process. The feeding motion can't be started until the sawing speed reaches the requirement of the system. Sawing speed is the tangential velocity of the chain which is determined by the speed of the saw motor. The speed of the motor can normally reach to 9000rev/min, and the chain speed can reach to 40 m/s.

Fig.3 shows the sketch of sawing operation. As shown in fig3, $\boldsymbol{u_d}$ is the sawing speed, $\boldsymbol{u_j}$ is the feeding rate which is controlled by the motion of the feed cylinder. $\boldsymbol{P}$ is the cutting resistance, which is the interaction between high speed chain and timber. Cutting resistance is influenced by the timber, sawing depth and feeding rate, and the direction is parallel to that of the chain speed. Many other parameters also influence the timber cutting, such as the material, shape, strength and rigidity of the chain saw, the character of timber, environmental conditions and so on.

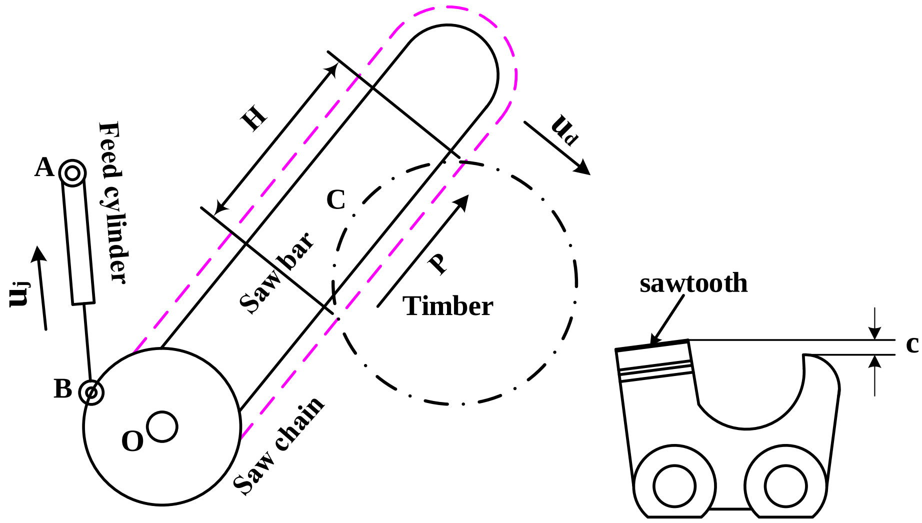


Fig.3

The sketch of cutting operation.

The cutting resistance can be expressed as follow [17]:

$$P = KeH\frac{u_d}{v} \tag{1}$$

Where K is coefficient of sawing resistance (kg/mm^2), e is thickness of chain saw (mm), H is the width of the contact between the chain saw and timber (mm), v is sawing speed (m/s). And sawing speed can be determined by:

$$v = \frac{\pi Dn}{60 \times 1000} \tag{2}$$

where D is the diameter of chain wheel(mm), n is rotate speed of hydraulic motor (r/min).

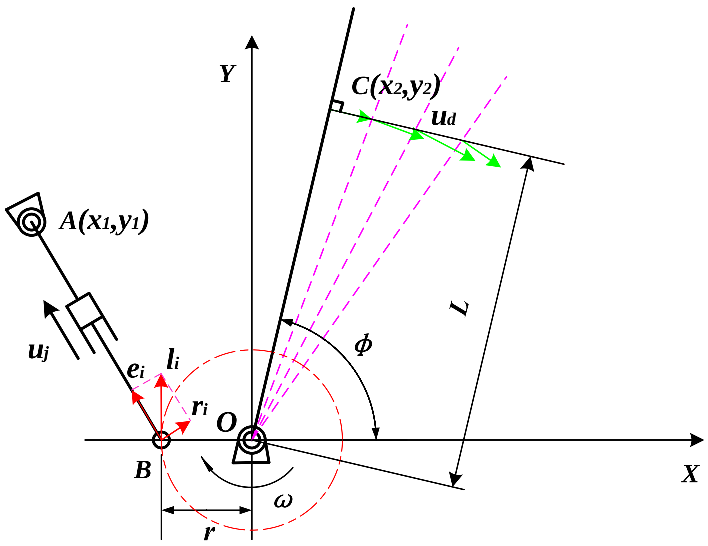


Fig.4 The kinematic model of cutting operation

Fig.4 shows the kinematic model of cutting operation. As can be seen in fig.4, the position of the motor rotation is marked as point *O*. A coordinate system *O-XY* is established for the kinematic model. In this model, feed cylinder is simplified as line *AB*, and the saw bar is simplified as line *OC*. In addition, ω is introduced in the cutting system as the rotated speed of the saw bar. Based on the kinematic analysis of the system, the key point *A*, *B*, *C* can be described as follow:

$$\begin{cases} A(x_1, y_1) \\ B(-r\cos\omega t, r\sin\omega t) \\ C(x_2, y_2) \end{cases} \tag{3}$$

Based on the equations of motion in the system. The feeding rate and the cutting speed have relationship with ω and the plane vector in this coordinate system. The relationships are expressed as follow [18]:

$$\boldsymbol{u}_j = (\boldsymbol{\omega} \times \boldsymbol{BO}) \cdot \boldsymbol{e}_i \tag{4}$$

$$\boldsymbol{e}_i = \frac{\boldsymbol{AB}}{AB} \tag{5}$$

$$\boldsymbol{u}_d = \boldsymbol{\omega} \times \boldsymbol{OC} \tag{6}$$

$$\begin{bmatrix} \cos\phi & \sin\phi \\ \sin(\phi-\omega t) & -\cos(\phi-\omega t) \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} L \\ 0 \end{bmatrix} \tag{7}$$

The feeding rate and cutting speed can be calculated in the following manner:

$$u_d = \frac{\omega L}{\cos(\phi-\omega t)} \tag{8}$$

$$u_j = \frac{\omega r\sqrt{(x_1 + r\cos\omega t)^2 + (y_1 - r\sin\omega t)^2}}{(x_1\sin\omega t + y_1\cos\omega t)} \tag{9}$$

Cutting speed is limited by the rate at which the cutting wood is removed, following is the ideal relationship between sawing speed and cutting speed,

$$\frac{v}{u_d} = \frac{m}{c} \tag{10}$$

Where m is pitch, c is greatest feed amount.

3.The simulation of 2-D Fuzzy control system for cutting operation

Now, with the development of simulation technology, more and more fields optimize the parameters by simulation methods. Fig.5 shows the simulation model of cutting hydraulic system of harvester head by AMESim[19], according to the working principle of the hydraulic cutting system. As can be seen in fig5, saw motor and feed cylinder are connected with variable pump, reversing valve 1, reversing valve 2 and compensated flow control valve 3 using hydraulic parallel connection.

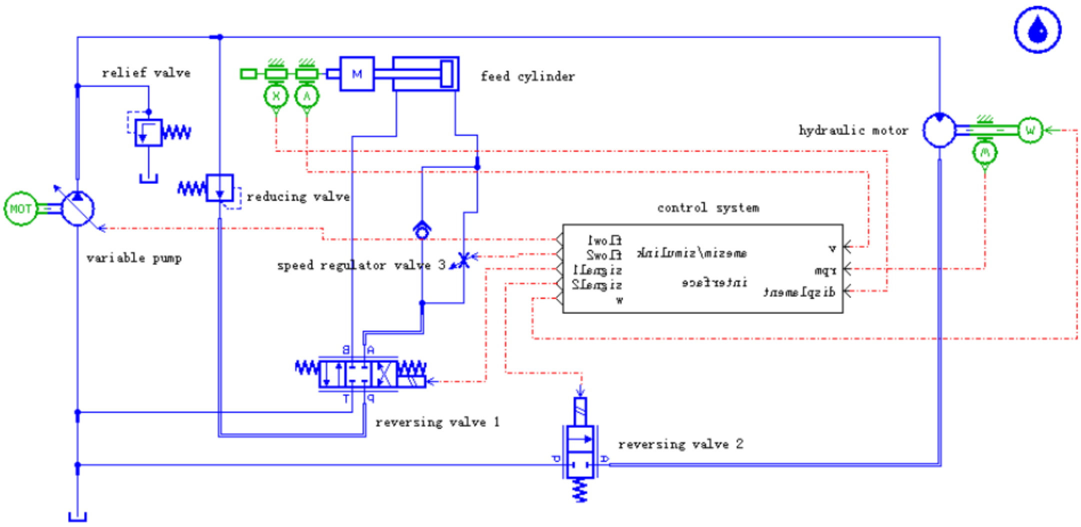


Fig.5 Simulation model of cutting hydraulic system

In fig.5, reversing valve 1 is used to adjust the scaling of feed cylinder, reversing valve 2 is used to control the switching of hydraulic motor, compensated flow control valve 3 is used to control the speed of feed cylinder. When the pump is working, the hydraulic motor rotates immediately and the feed cylinder begins to act. The speed and displacement of the feed cylinder and the speed of the pump are the inputs of the control system. Reversing valve 1, reversing valve 2, speed regulator valve 3 and variable pump are adjusted by the control system.

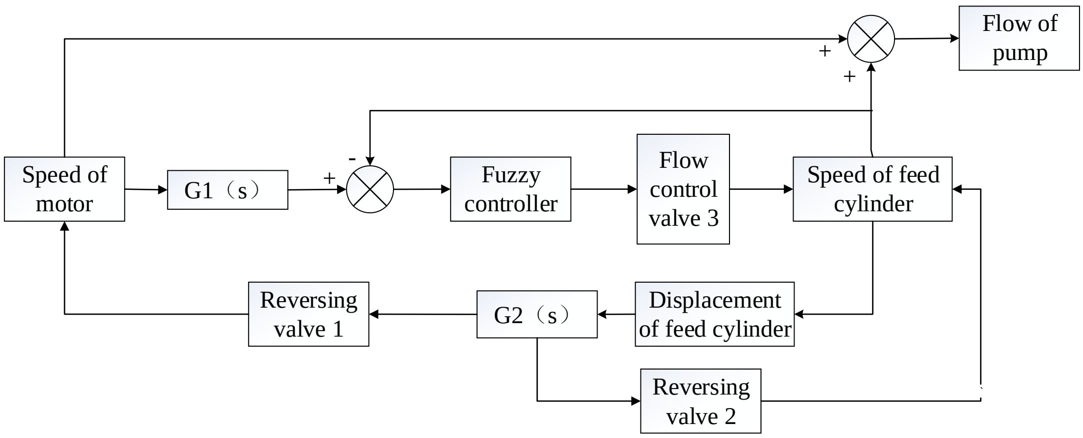


Fig.6 Strategy of cutting hydraulic control

Fig.6 shows the control strategy of the system, as can be seen, the hydraulic control system is based on closed-loop feedback system. Speed of motor is the input of the control system, and the speed of the feed cylinder is controlled by flow control valve 3 through G1(s) and fuzzy controller. Through integration, the displacement of feed cylinder is obtained from speed of feed cylinder. Speed of motor is also influenced by the reversing valve 1 through G2(s). The summation of the speed of motor and speed of feed cylinder is the flow of the pump. In this system, it is the key technique to control the speed of feed cylinder.

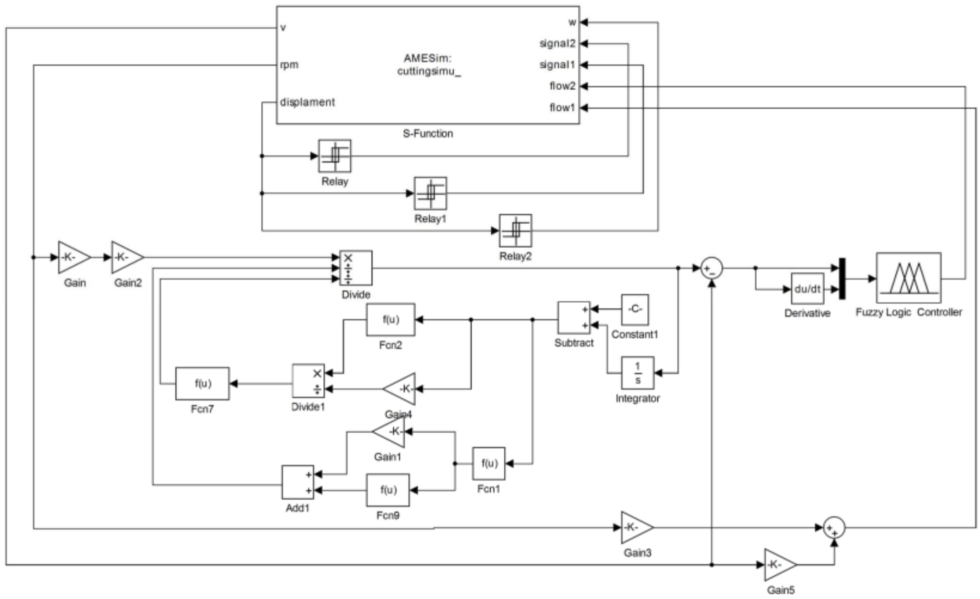


Fig.7 Simulation model of cutting hydraulic control

Fig.7shows the hydraulic control system established in Matlab/Simulink[20]. The inputs are rotate speed of hydraulic motor, speed of feed cylinder and displacement, the output is the signal of reversing valve 1, reversing valve 2, flow control valve 3 and the variable pump. The output signals are regulated and controlled by fuzzy controller during the whole cutting process.

Referring to the article [21], the fuzzy control system adopt the 2-D fuzzy control as the core controller, and this time the controller is used in the harvester cutting process. The input of the fuzzy controller are the deviation (RD) and the change of the deviation (RDC) between the actual value and the ideal value of the feed cylinder's rate. The output of the fuzzy controller is the signal (K) of the flow control valve 3.

The linguistic variables for deviation (RD)are ; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and it is quantized into 7 levels represented ranged from -0.02 to 0.02, the linguistic variables for change of deviation (RDC) are :Fast Left (FL), Medium Left (ML), Slow Left (SL), Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized through -3 to 3,and the linguistic variables for the signal (K) of the flow control valve 3 are Zero (ZE), Very Small (VS), Small (S),Small Big (SB), Medium Big (MB), Big (B), and Very Big (VB) and they are ranged from 0 to 1. In this research triangular membership function is selected and the input and output function are shown in fig. 8 to fig. 10.

The rule base for the cutting operation feeding rate mode controller has the form:

R_1: IF RD is NB and RDC is FL, THEN K is S.

There are n×n rules in a fuzzy base. The complete rule base for supervisory controller is shown in Table 1.

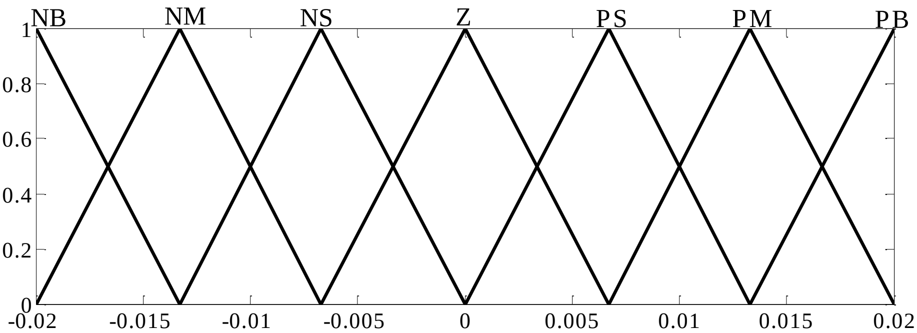


Fig.8 Membership function curves of RD

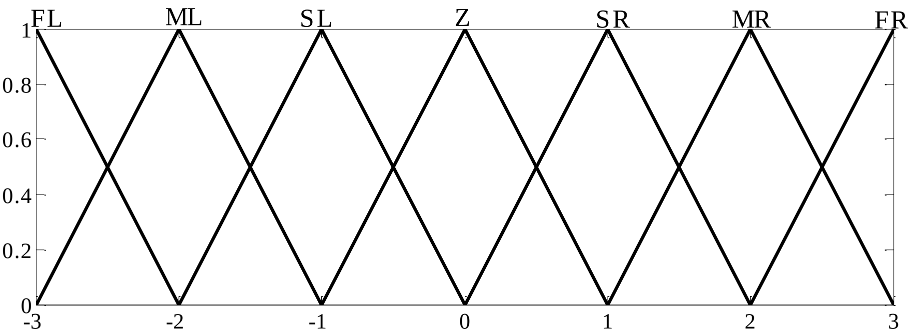


Fig.9 Membership function curves of RDC

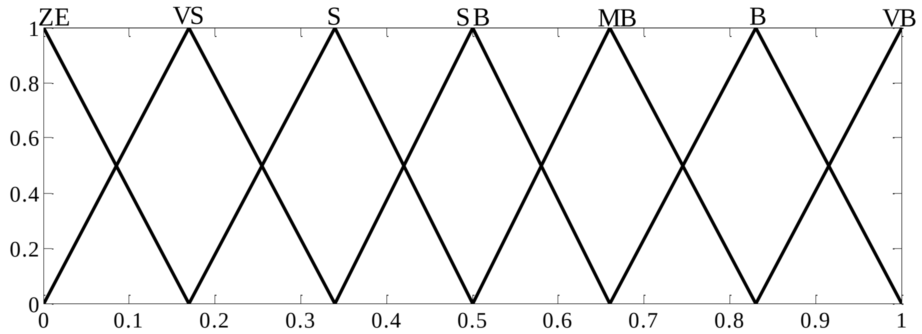


Fig.10 Membership function curves of K

Table 1

Fuzzy rule base for cutting operation

RDC / RD	FL	ML	SL	Z	SR	MR	FR
NB	S	VS	VS	ZE	ZE	ZE	ZE
NM	S	S	VS	VS	ZE	ZE	ZE
NS	SB	S	S	VS	ZE	ZE	ZE
Z	SB	SB	S	S	VS	ZE	ZE
PS	B	B	SB	SB	S	VS	VS
PM	VB	VB	B	SB	S	S	S
PB	VB	VB	VB	B	SB	SB	S

4. Results

To make the research simple, this simulation ignore the influence of texture, shape, strength and rigidity of chain saw, timber characteristics, and environmental conditions and so on. Take the eucalyptus as the cutting object, the diameter is 300mm, rotate speed of hydraulic motor is constant.

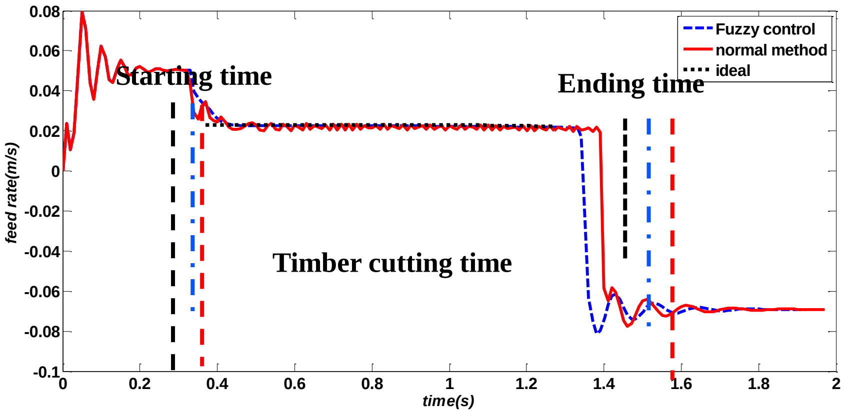
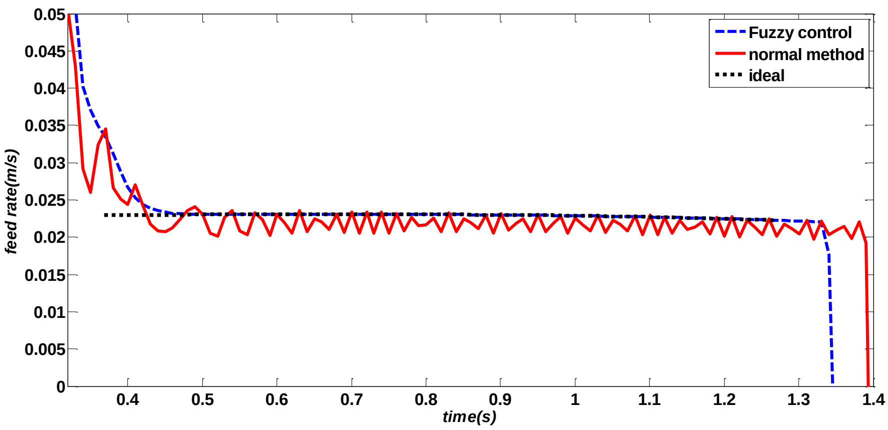
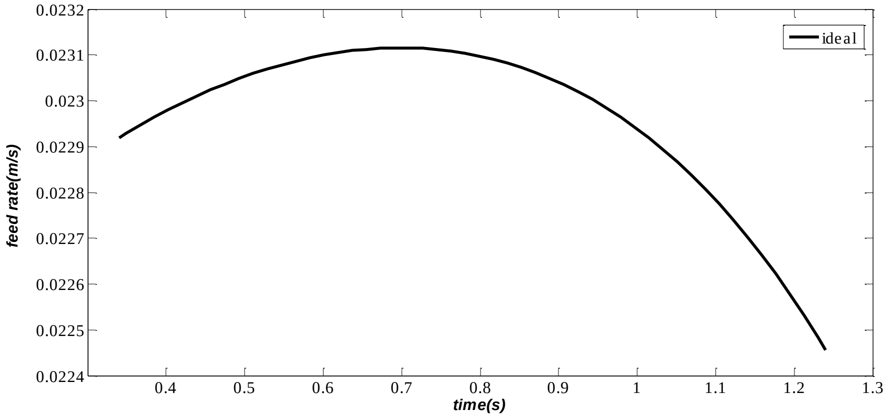


Fig.11 Feeding rate during the whole cutting operation

Fig.11 shows the feeding rate of the cylinder during the cutting operation, the three curves in the graph represent three control conditions: ideal, fuzzy control and normal method respectively. As can be seen in fig. 12, at the beginning of the simulation, the flow control valve 3 is open completely, the feeding rate rises to 0.08m/s, but when it is going to cut the timber, the feeding rate line drops down. With the control of fuzzy, the feeding rate line goes smoothly and the starting time (0.36s) is earlier than that with the normal method (0.37s). Also the ending time is 1.34s under the fuzzy control, which is faster than that under the normal method, then the cylinder returns at the same rate. The whole operation finished within 2s. During the whole operation, it takes 1.93s to finish the job by fuzzy control and 0.05s was saved.



a) The whole curve of the feed rate



b) Zoom curve for the ideal feed rate

Fig.12 Feeding rate during the timber cutting operation

In normal method, no special control was used, so that the feeding rate drops down when the saw bar kicks the timber heavily. As shown in fig.12, the feeding rate with the normal method changed very quickly, and it swings below the ideal feeding rate all the time. But with fuzzy control the feeding rate can fit the ideal line very well, so it is the reason why fuzzy control can save time and quicker than the normal method. Generally speaking, an eucalyptus tree will be cut into 5 sections, and 5 times cutting operations, 4 times timber feeding operations are needed in the whole process. Fig.13 shows variation of feed cylinder displacement during a whole tree cutting operation. Normally feeding time was about 2s, a tree cutting operation costs 17.65s and 0.25s was saved by fuzzy control. Cutting efficiency is increased by 1.4%

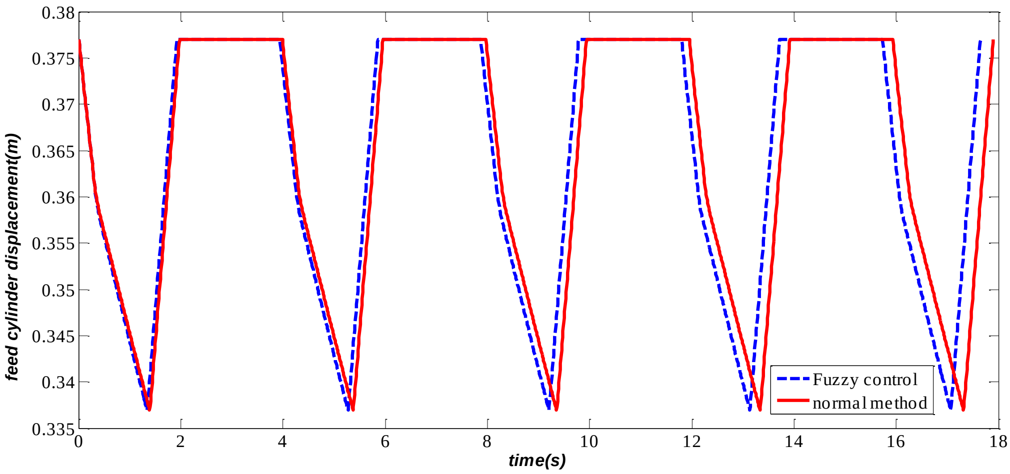


Fig.13 Variation of feed cylinder displacement during a whole tree cutting operation

At the same time, fuzzy control can also save energy. Fig.14 shows that it needed 35.18 kJ to complete one cutting operation. Only considering cutting motion, the hydraulic system energy consumption is 41.67 kJ under the normal method. Under the fuzzy control, as the cutting time decreases, the energy consumption on the valves drops down. So hydraulic system energy consumption is 39.77 kJ during one cutting operation. The energy consumption is decreased by 4.5% with the fuzzy control method.

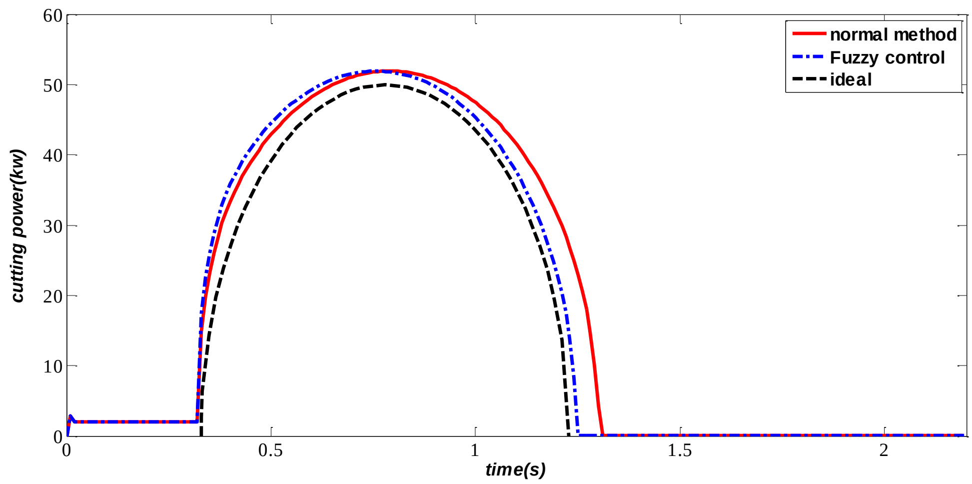


Fig.14 Energy consumption in the cutting operation

5. Conclusion

Quick cutting process is always the main purpose of the timber cutting system. How to make the cutting time as short as possible is the task of the paper. Cutting speed is the key for the cutting time, so the kinematic model of cutting operation is established. The old method did no special on the cutting speed, so a new fuzzy control strategy is developed firstly in the paper, and the simulation model is set up by AMEsim and Simulink/matlab platform.

As the result of the simulation, the following conclusion can be presented:

1. Based on the kinematic model, the ideal cutting speed proved to be related with the feeding rate, rotating speed of hydraulic motor and the position of the saw bar and feed cylinder, and it is a nonlinear system.

2. During a tree cutting operation, the fuzzy control strategy which can control the feeding rate is more closed to the ideal feeding rate than the normal method, the time was saved 0.25s, efficiency was increased by 1.4%.

3. 2-D fuzzy controller can also save energy during the cutting operation. Because of the faster cutting, this method can reduce the energy consumption during the valves and the pipes, and energy consumption was decreased by 4.5%.

This is the beginning of the harvester head cutting system study, only idealized model was established in this paper. In the next step, a comprehensive cutting system model will be built. In next step, with the accumulation of the data, material, shape, strength and rigidity of the chain saw, the character of timber, environmental conditions will be explored and introduced into this model, and the simulation will get a more accurate result.

6. Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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R E F E R E N C E S

[1] *T Virvalo;J Inberg*. “Feed force based constant torque control of hydraulic motor in Chainsaw application.”PTMC, September 1-3. pp. 173-186.(2004)

[2] *Iwaoka, M., Aruga, K., Sakurai, R., Cho, K. H., Sakai, H., & Kobayashi, H*. “Performance of small harvester head in a thinning operation”. Journal of Forest Research, Vol. 4, pp.195-200 (1999).

[3] *Inberg, J., Virvalo, T., &Einola, K*. “Design aspects of timber cutting hydraulics in a single-grip harvester.” SAE Technical Papers. Vol.3 (2002).

[4]. *Dote, Y.* (1995). “Introduction to fuzzy logic.” 21st International Conference on Industrial Electronics, Control, and Instrumentation. pp. 50-56 (1995).

[5] *Huashi, L, Baoling, L. Sheng, Q.&Shufeng.W.* “Simulation of all-wheel steering for three-axle vehicle based on fuzzy control”. Transactions of the Chinese Society of Agricultural Engineering Vol.13.pp 34-41. (2012)

[6] *Ma, L. S. a*. “Stability Analysis and Controller Design of Discrete Interval Type-2 Fuzzy Systems.” Asian Journal of Control, AUG, pp. 1–14. (2013)

[7] *Feng, J. E., Lv, H. L., & Cheng, D. Z.* (2013), “Multiple fuzzy relation and its application to coupled fuzzy control”. Asian Journal of Control Vol.15, pp.1313-1324.

[8] *Menhaj, J. K. a. M. B.*. "From nonlinear to fuzzy approaches in trajectory tracking control of wheeled mobile robots." Asian Journal of Control Vol. 14, No. 4: pp. 960–973. (2012)

[9] *Wang, S., Ying, J., Zhou, W., &Ke, M*. “Fuzzy control of the ram velocity in energy-saving servo injection molding machines”, International Technology and Innovation Conference, Xi'an, China.(2009)

[10] *Song Le-peng, Dong Zhi-ming, Xiang Li-juan, Xing Si-yuan*, “Variable universe adaptive fuzzy PID control of spray flow valve”.Transactions of the CSAE,Vol.11, pp.114-118(2010)

[11*] Chiang, M.-H*, “The velocity control of an electro-hydraulic displacement-controlled system using adaptive fuzzy controller with self-tuning fuzzy sliding mode compensation.” Asian Journal of Control, Vol. 13, No. 4, pp. 492-504.(2011)

[12] *Zhanzheng, G.Shihua, Y. Chongbo, J. &Chao*, W.“Modeling and simulation of shifting process in hydraulic machinery stepless transmission based on AMESim”,Transactions of the CSAE, Vol.10, pp.86-90(2009)

[13] *Borboni, A.*, Solution of the inverse kinematic problem of a serial manipulator by a fuzzy algorithm(2001) IEEE International Conference on Fuzzy Systems, 1, pp. 336-339.

[14] *N. Jabbour and C. Mademlis*, "Improved Control Strategy of a Supercapacitor-Based Energy Recovery System for Elevator Applications," (2016) IEEE Transactions on Power Electronics, vol. 31, pp. 8398-8408, 2016-01-01.

[15] *M. M. Aly, M. Abdel-Akher, S. M. Said, and T. Senjyu*, "A developed control strategy for mitigating wind power generation transients using superconducting magnetic energy storage with reactive power support," (2016). International Journal of Electrical Power and Energy Systems, vol. 83, pp. 485-494.

[16] *Tervo, K., Palmroth, L., &Putkonen, A.* (2009). “A hierarchical fuzzy inference method for skill evaluation of machine operators.” IEEE/ASME International Conference on Advanced Intelligent Mechatronics, (2009)

[17] *Longbin, M*., Forest cutting machines and tools. China Forestry Publishing House, Beijing, pp.185-187, (1991)

[18] *Zixing, C*., Robotics. Tsinghua University Press. Beijing.pp. 66-70(2000)

[19] *Yongling, F. Xiaoye, Q.*, Modeling and Simulation of LMS Imagine. LabAMEsimSystem. Beihang University Press,Beijing(2011)

[20] *Defeng, Z.*, Modeling and Simulation of MATLAB/Simulink. China machine press, Beijing(2010)

[21] *Xin, Z., Jinhao, L., Dian, W.*, Design and simulation of fuzzy self-adjusting PID controller(2010) 2010 International Conference on Computing, Control and Industrial Engineering, CCIE 2010, 2, art. no. 5491972, pp. 28-31.