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Research on the Energy Error Control Algorithm Based on the Differential Equation Model

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Abstract: According to the torque balance principle and circuit analysis theory, this study established the model that motor driving current relying on observable rotate speed and torque. The classical computer control method in which current relying on rotate speed difference can't properly calculate the current value, the differential calculation of rotate speed make the circuit into a feedback system, the performance is unstable. Through the differential equation model, this study redesigned the control algorithm to calculate the motor's parameter and then using the rotate speed and torque which can be observed to make the transformation of variables. Finally, the experiment shows that this energy error control algorithm can well make real-time control of current value.

Key words: Electric control, real-time control Feedback loop, MATLAB, computer control system

INTRODUCTION

Car braking is the device which is used to enforce moving slowly and make the speed of vehicle stable (Baek and Veciana, 2005). With the rapid development of the highway and the improvement of traffic density, in order to guarantee safety, the work reliability of car braking system is more important than before. Only the car's brake performance is good and its brake system is reliable (Srinivasan *et al*., 2004). Brake is the actuator which is used for hinder vehicle's movement or trend of the movement in automobile brake lines (Yin and Lin, 2005).

Automobile braking bench testing simulated the brake process of the automobile (Busse *et al*., 2006; Foulds, 1984). At present, the classical method is using inertial dynamometer to simulate the brake assembly braking condition and test its various performances (Anastasi *et al*., 2006). According to references, the classical computer control method in which current relying on rotate speed difference can't properly calculate the current value. The differential calculation of rotate speed make the circuit into a feedback system, the performance is unstable. Through the differential equation model, this study redesigned the control algorithm to calculate the motor's parameter and then using the rotate speed and torque which can be observed to make the transformation of variables.

BRAKE DRIVING MODEL

Firstly, these devices such as electric motor, spindle of fly wheel, electric motor which driving spindle and auxiliary devices which braking on the brake testing stage will be simplified as shown in Fig. 1.

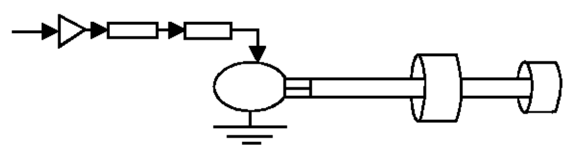

Fig. 1: Equipments which are on brake test stage

According to torque balance principle and circuit analysis theory, can get the two ordinary differential equations to describe the relationship between the input voltage and output angle (Jobnson *et al*., 2004):

$$\begin{cases} L\frac{dI(t)}{dt}+k_b\frac{d\theta(t)}{dt}+RI(t)=U(t) \\ J\frac{d^2\theta(t)}{dt^2}-k_\tau I(t)=T_s \end{cases} \tag{1}$$

where, U (t) is the input voltage, I (t) is the generate electricity value; T_d is the coil current produces; J is the total inertia of the system. The rotor with angle θ (t) likes as motor, produce the reserve voltage. R is the impedance of the motor; L is the current of coil; k_b is the reverse electromotive force constant; T_S is the brake torque; k_t is the transformation factor from current to torque. According to the data, the current and the torque are in direct proportion and scale factor is 1.5 (Wu *et al*., 2010).

The current and torqueses are in direct proportion, can establish the relationship that motor driving current zelying on observable speed n_t and torque T_d (t):

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$$\begin{cases} L\frac{dI(t)}{dt}+k_b n(t)\frac{2\pi}{60}+RI(t)=U(t) \\ \frac{2\pi}{60}J\frac{dn(t)}{dt}-T_d(t)=T_s \end{cases} \tag{2}$$

$$\Rightarrow I(t)=\int_0^t \frac{U(t)-R\,T_d(t)/k_\tau-k_b n(t)\frac{2\pi}{60}}{L}dt$$

Input voltage is depending on the specific circumstances. During the process of braking on test stage exists the following relationship (Zhou *et al*., 2008):

$$T(t)=J\frac{d\omega(t)}{dt} \tag{3}$$

where, T (t) is the total brake torque; J is the equivalent rotate inertia.

For the simulation process, there are two situations as follows: mechanical inertia can satisfy the equivalent rotate inertia, J completely consists of mechanical inertia J_f; Mechanical inertia can't satisfy the equivalent rotate inertia, J consists of mechanical inertia and motor simulation inertia:

$$J = J_f+J_d \tag{4}$$

$$T(t)=J\frac{d\omega(t)}{dt}=(J_f+J_d)\frac{d\omega(t)}{dt}=J_f\frac{d\omega(t)}{dt}+J_d\frac{d\omega(t)}{dt}=T_f+T_d \tag{5}$$

$$\begin{cases} T_d(t)=\frac{2\pi}{60}J_d\frac{dn(t)}{dt}=T(t)-T_f(t) \\ I(t)=\int_0^t \frac{U(t)-R\,T_d(t)/k_\tau-k_b n(t)\frac{2\pi}{60}}{L}dt \end{cases} \tag{6}$$

where, T_f is the torque of flywheel and shaft; U (t) is input voltage; R, L, k_b are constants.

EVALUATION MODEL BASED ON ENERGY ERROR

During the process of braking, t_0 is the moment when brake torque start work, E is the consumed energy:

$$E=\int_{t_0}^{t} T_s\omega dt$$

where, ω is the angular velocity during the process of wheel braking. From:

$$\beta=\frac{d\omega}{dt}=\frac{T_s}{J}$$

can get the brake torque is:

$$T_s=J\beta=J\frac{d\omega}{dt}$$

$$E=\frac{1}{2}J\left(\omega_t^2-\omega_{t_0}^2\right) \tag{7}$$

where, J is the equivalent inertia; ω^2_{t0} is the angular velocity of wheel at the beginning of braking, ω^2_t is the angular velocity of wheel at the end of braking, during the process of vehicle testing brake, the consumed energy from t to t+Δt as following:

$$E_L=\frac{1}{2}J\left(\omega_{t+\Delta t}^2-\omega_t^2\right) \tag{8}$$

In the process of the test on the brake test stage, the consumed braking energy is:

$$E_S=\frac{1}{2}J\left(\omega_2^2-\omega_1^2\right) \tag{9}$$

On the brake testing stage which mechanical inertia can accurately simulates the equivalent inertia, J is got from the combination of flywheel on the testing stage; on the brake testing stage which mechanical inertia can't accurately simulates the equivalent inertia, J is got from the rotation inertia and the rotation inertia which motor analog compensation. Therefore, motor need to output torque and output torque need to meet the following condition: T_d and J_f work together, guaranteeing the consumed energy in the process of braking is equivalent to the consumed energy in J separate function.

In the process of testing on the brake test stage, the instantaneous torque of the spindle can be measured objectively. Therefore, this study can calculate the required energy consumption starting from torque. By the relationship between power and torque P = Tω, can get that the energy of a period of times calculated as follows:

$$E_r=\sum_i Pt_i=\sum_i\left[T_f+T_d(t_i)\right]\omega t_i=\sum_i T(t_i)\omega t_i \tag{10}$$

As long as the data T (t_i) during the testing can be measured, then the consumed energy in the actual braking process can be get.

No matter what control method, they all aim at making the motor's missing energy E0 T ($_i$) = T_d (t_i) ωt_i. In a period of time, the difference between the missing energy due to lack of mechanical inertia and the compensation for energy in practice is the absolute energy error in a period of time: ΔE = E_S-E_t. The relative energy error is as following:

$$e=\frac{\left(E_s-\sum_i T_f\omega t_i\right)-\sum_i T_d(t_i)\omega t_i}{E_s-\sum_i T_f\omega t_i}=\frac{E_s-E_t}{E_s-\sum_i T_f\omega t_i} \tag{11}$$

The energy error is an important quantitative indicator of the evaluation control methods.

According to the experimental data, using established evaluation model based on the energy error, to obtain the difference ΔE (t) between the energy consumption in road test and the energy consumption on testing stage.

From the Fig. 2, calculating the steady state of this problem appears after 1 sec. So treating t = 1 sec as the initial point of brake reaching a steady state on the test stage is feasible. In addition to the extremely individual time, the difference ΔE (t) between the energy loss of the road test and the test stage are maintained within the range of [300, -300] and the difference scope is shrinking, the difference decreases. From the above analysis results, the control method in title can't ensure supply braking energy in accordance with the relationship of time function:

$$E = \int_{t_0}^{t} T_s \omega dt$$

Though, there is deviation of energy consumption between road test and the test stage in each time, through the analysis and comparison between the energy consumption while road testing E_r = 52163.58 (J) and the energy consumption on the test stage E_r = 52163.58 (J) in entire braking process, this model can get the absolute value of relative energy error |e| = 21.05%; If the analysis process start from the initial moment of entering the steady state, this model can get the absolute value of relative energy error |e| = 4.67%. Thus, the braking process which in road test and on test stage in the whole brake state and stable state, respectively has That is when the road test the braking process simulation and test on the stage of braking process, in the whole brake state and stable state respectively has consistency of 70% and 97.72%. Using the control method in title, better guarantee the consumption energy under the joint action of the motor output torque T_d and the rotation inertia of flywheel J_f is equivalent to the consumed energy in J separate function.

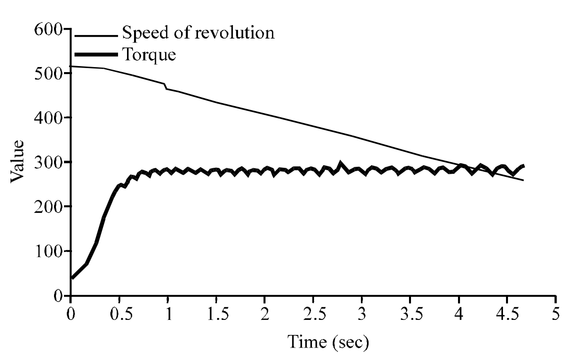

Fig. 2: Speed and torque changing over time

COMPUTER CONTROL METHOD BASED ON DIFFERENCE

From $T_d = J_d d\omega(t)/dt$, I (t) = 1.5 T_d, ω (t) = n (t)×π/30, J_d = J-J_f the value of motor current is: I (t) = (J-J_f)×πdn (t)/(30 dt). For the above model, when the value of time Δt is small enough, according to the rotate velocity at last moment to design the computer control method during this time among them, J and J_f are determined relying on the system.

According to the experiment data and using the established model, the current value of this time according to the observed Instantaneous speed of the previous time can be calculated. Then this study uses evaluation method to evaluate the control method which relying on difference. The index of energy error in the process of evolution as shown in Fig. 3.

The figure shows that the braking energy loss difference of road test and test on the stage have some regularity. In each time, the energy consumption on test stage is more than in road test. When time t in the range of [0.981], energy error ΔE (t) reach a negative peak value 461.197 J after 1 sec, the fluctuation range of the energy error is growing, tending to increase. Therefore using the control method relying on difference can't well ensure supplying needed energy according to the relationship which is same as time factor:

$$E = \int_{t_0}^{t} T_s \omega dt$$

so there is defect in the control method relying on difference.

If directly using the formula $T_d = J_d \omega$ (t) 1 dt to simulate the inertia which transform from system energy that is supplied by motor, there are two defects as follows: in order to get πdn (t)/(30 dt) in the formula, the difference calculation on observed rotate velocity should be on the test stage; Due to using dω (t)/dt, So, the inertia loop is a feedback system, need to make difference computation

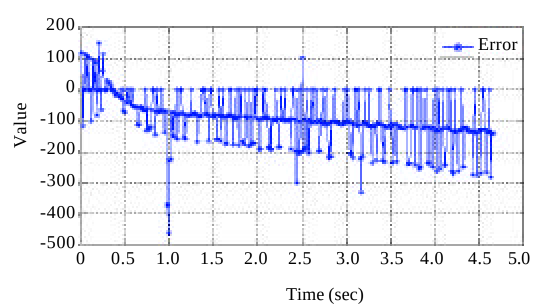

Fig. 3: The energy error ΔE(t) of the control method relying on the difference

according to the real-time data speed. If the measurement data produce deviation, which is very easy to produce instability, the system will produce unexpected damage.

NON DEPENDENT DIFFERENTIAL COMPUTER CONTROLLED MODEL

In order to design the computer control method of this time according the observed instantaneous speed or instantaneous torque of previous time:

$$L\frac{dI(t)}{dt}+k_b\omega(t)+RI(t)=U(t) \tag{12}$$

Because, of the complexity of brake performance, it is very difficult to get the precise relationship between motor driving current and time; the difference processing method which is commonly used in engineering:

$$L\frac{I(t+\Delta t)-I(t)}{\Delta t}+k_b\frac{d\theta(t)}{dt}+RI(t)=U(t)\Rightarrow I(t+\Delta t) =\left[U(t)-k_b\omega(t)-RI(t)\right]\frac{\Delta t}{L}+I(t) \tag{13}$$

For the input voltage, use effective voltage U, considering it as a constant item, R, L and k_b is constant then the above formula can turn into:

$$a\frac{I(t+\Delta t)-I(t)}{\Delta t}+b\omega(t)+cI(t)=1 \tag{14}$$

$$a=\frac{L}{U};\ b=\frac{k_b}{U};\ c=\frac{R}{U}$$

now using the experimental data obtained by the relevant control methods to identify parameters by least-squares fitting, the specific process as follows: According to the rotate velocity n (t), using ω (t) = n (t)×π/30 a group value of ω (t) can be get; According to the proportion of torque generated by the current and the motor, the motor driving current I (t) = 1.5 T_d (t) = 1.5 (T(t)-T_s (t)). At this moment:

$$\frac{I(t+\Delta t)-I(t)}{\Delta t},\ \omega(t)\text{ and }I(t)$$

are all found out, they are a group of columns.

Using MATLAB programming to identify the parameters, a = 3.6735×10^5, b = 0.0243 and c = 0.0085. Then the current value I(t+Δt) of this time according to the instantaneous speed n(t) and the instantaneous torque T(t) of previous time can be calculated, specific process as follows:

$$I(t+\Delta t)=\left[1-b\omega(t)\right]\frac{1}{a}\Delta t+\left[1-\frac{c}{a}\Delta t\right]I(t) \tag{15}$$

$$I(t+\Delta t)=\left[1-0.0243n(t)\frac{2\pi}{60}\right]\frac{0.01}{3.675\times10^{-5}}+1.5\left[T(t)-276.6535\right] \tag{16}$$

The current value I (t+Δt) of this time according to the instantaneous speed n (t) and the instantaneous torque T (t) of previous time can be obtained.

According to experiment data, using the current computer control model this study established, according to the instantaneous speed and the instantaneous torque of previous time to calculate the current value of this time, so this study can computer control the current value. The method of model evaluation as follows:

Firstly, this study calculate the current value I_c(t) of each 0.01 sec according to rotate velocity and torque; and using I_c (t) to calculate the torque T_{cd} (t) generated by the driving current, then this study can the total torque T_c (t); At last, using evaluation criterion to compare the energy consumption between which on the test stage and in actual road test under the control method .

Although, there is deviation between energy consumption which in road test and on the test stage in each time, through the comparison between the energy consumption in road test E_r = 52163.58 and the energy consumption on the test stage E_r = 56419.88 in entire braking process, this model can get the absolute value of the relative energy error |e| = 30.13%; if the analysis process start from the initial moment in a stable state, the absolute value of the relative energy error is |e| = 3.28%. Thus, the braking process which in road test and on test stage in the whole brake state and stable state respectively has That is when the road test the braking process simulation and test on the stage of braking process, in the whole brake state and stable state respectively has consistency of 70 and 97.72%.

The control method this study designed well ensures the consumption energy under the joint action of the motor output torque T_d and the rotation inertia of flywheel J_f is equivalent to the consumed energy in J separate function.

INFERENCE

The evaluation indicator energy error, according to two powerful evaluation criteria: the motor output torque T_d and the rotation inertia of the fixed flywheel J_f work together, guaranteeing the consumed energy in the process of braking is equivalent to the consumed energy in the separate function of the equivalent inertia J; the motor output torque T_d and the rotation inertia of the fixed flywheel J_f work together, ensuring supply braking energy in accordance with the relationship of time function:

$$E = \int_{t_0}^{t} T_s \omega dt$$

This model can make effective evaluation and analysis on the control method and its results of implementation. The energy error is an important factor of evaluation control method, so set it as evaluation index and then this study can come up with a reasonable result of the evaluation. But the index which judging the quality of evaluation control method is more than a energy error, while the evaluation model based on energy error just use the energy error index, did not take the influence of other indicators into account , this is the disadvantage of the model.

This study firstly established the current computer control model which dependents on difference, however, when use the established evaluation index to judge the calculation result of this model, which is not very ideal. Therefore this model needs to be improved in order to get a model which meets the two energy standards. In view of the defects of the current computer control model which relying on the difference, this study established the current computer control model which is independent on the difference, this model avoids system instability and since the feedback effect brought by the difference and get the current computer control method which is agree with the actual results of road test.

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