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Project of a Micropositioning System for a Roundness Measuring Machine

Leonardo Massunari Lieu [1], *Agenor de Toledo Fleury* [12]

[1] IPT, Brazil, São Paulo, leonardo@ipt.br
[2] USP, Brazil, São Paulo, agfleury@ipt.br

Abstract: This work presents the design of a X-Y table, which features a "Deadbeat" type controller to be used as an auxiliary device in a roundness measuring machine.

In order to give evidences and to complete the development of this work, several numerical simulations have been executed through the timing of the work and a prototype has been built to test the concepts**.**

Keywords: Precision control, Micropositioning control

1. INTRODUCTION

A 2 axis (X-Y) table is to be used in a roundness measuring machine or any other dimensional measuring equipment, where high precision positioning is needed.

The micropositioning 2 axis table has been developed to centralize automatically a roundness standard. Its functionality has been certified by the construction of a prototype which does not feature all the details studied but presents enough resources to attend and support the desired application.

The positioning control is based on a discrete time "Deadbeat" type controller, which theoretically provides high performance precision response. Always minding that micropositioning depends on actuator saturation and friction.

Furthermore, a Kalman filter based methodology has been developed in order to estimate the true position of an electronic pick-up, used to get the form measurement error in a circularity measuring equipment.

2. PURPOSE

Roundness standards, widely used in industries to calibrate roundness measuring machines can be found in many sizes with high roundness precision in their nominal diameters. In order to make possible the calibration of these roundness standards, high precision roundness measuring machines are used, in order to make possible roundness error measurement with a resolution close to 0.01 µm.

The main purpose of this work consists on the design of a micropositioning system to centralize the roundness standard in relation to the rotation axis of a machine that has quite a few automatic auxiliary devices. The machine, a Talyrond model 51 of the 1960s, has a high precision in its mechanical concepts and this study aims to improve the performance of this machine.

An expected positioning with accuracy nearly to 1 µm, will allow the use of an electronic pick up in its best measuring range, minimizing error and contributing to determine the roundness error of the roundness standard by direct measurement. Besides the micropositioning, the rotation of the roundness standard around its longitudinal axis each 30° until a complete cycle, after each measuring cycle, allows to use algorithms able to determine the error of the set composed by the rotation axis and the table.

The positioning requirements to be satisfied by the system are: movement of a 1 kg roundness standard, with an accuracy close to 1 µm and range of 5 mm. The table has to be actuated by independent DC motors (one motor for each axis), to allow the movement of the roundness standard in two Cartesian axis (X-Y). The closed loop system must give a precision positioning in the expected range from a reference generated through the electronic pick up. The computer receives the position signals from the displacement sensors which are linked to the table, where they are processed through the computer and analog signals are emitted. These signals go through an electric circuit where they are amplified to feed the DC motors which are in charge to move the table to the desired position. The X-Y table is basically composed by two mounting plates with independent and perpendicular movement.

3. METHODS

The concept of "Deadbeat" response is unique to discrete-time control systems. In "Deadbeat" control, any nonzero error vector will be driven to zero in at most *n* sampling periods, where *n* corresponds to the system order. From the other side, it is not physically possible to increase the magnitude of the control signal without a bound. If this magnitude is increased without constraints, the saturation phenomenon always take place (Ogata, [3]).

Each axis of the table has been modeled considering the transformation of rotary to translational motion through a pinion-rack system, actuated by DC motors. In this way, the motion equations can be written as:

$$\begin{aligned} & m*\ddot{x} + b*\dot{x} = F_{ext} \\ & J*\ddot{\gamma} + b_p*\dot{\gamma} = -\tau_{ext} + K_t*i \\ & R_a*i_a + L_a*\frac{di_a}{dt} + K_v*\dot{\gamma} = U \end{aligned} \qquad (1)$$

where:

m : mass of the table
b: table viscous friction
F_{ext}: external forces considering the nonlinearities and frictions
J : system inertia
b_p : pinion-rack viscous friction
τ_{ext} : motor torque of the pinion
K_t : torque constant
R_a : motor resistance
L_a : motor inductance
K_v : back EMF constant
U : electric motor feed voltage (saturated in 2 V)
i_a : motor current
γ: pinion angular displacement

The above differential equation system in state-space standard form, is represented as:

$$\dot{x} = A * x(t) + B * u(t)$$
$$y(t) = C * x(t) \qquad (2)$$

or,

$$\begin{bmatrix} \dot{\gamma}_x \\ \ddot{\gamma}_x \\ \dot{i}_{ax} \\ \dot{\gamma}_y \\ \ddot{\gamma}_y \\ \dot{i}_{ay} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{-BM_x}{Am_x} & \frac{K_t}{Am_x} & 0 & 0 & 0 \\ 0 & \frac{-K_v}{L_a} & \frac{-R_a}{L_a} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \frac{-BM_y}{Am_y} & \frac{K_t}{Am_y} \\ 0 & 0 & 0 & 0 & \frac{-K_v}{L_a} & \frac{-R_a}{L_a} \end{bmatrix} * \begin{bmatrix} \gamma_x \\ \dot{\gamma}_x \\ i_{ax} \\ \gamma_y \\ \dot{\gamma}_y \\ i_{ay} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_a} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{L_a} \end{bmatrix} * u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} * \begin{bmatrix} \gamma_x \\ \dot{\gamma}_x \\ i_{ax} \\ \gamma_y \\ \dot{\gamma}_y \\ i_{ay} \end{bmatrix} \qquad (3)$$

where,

$$BM = b_p + \frac{(B * p^2)}{(4 * \pi^2)}$$

$$Am = \left(J + \frac{m * p^2}{4 * \pi^2} \right)$$

and the output vector y includes γ_x and γ_y measurements.

Calling the matrix K as the state feedback gain matrix, K_e as the observer feedback gain matrix and choosing all eigenvalues of |A-B*K| to be zero, it is possible to get the deadbeat response. Then,

$$| s*I - A + B*K | = 0 \text{ and } | s*I - A + C*K_e | = 0, \qquad (4)$$

3.1. Nonlinear model

Nonlinearities must be included in the model to improve the performance of a control system, mostly if a high accuracy is needed at a low signal level. The nonlinear friction can be described as a combination of static friction (f_s) and coulomb friction (f_c), phenomenon that occur when two surfaces are in contact with a sliding or rolling motion. In this case, the nonlinear phenomena is related to the table and motor friction. Static friction exists only if the velocity is zero and the net applied force does not exceed the breakaway value, f_s. The Coulomb friction is smaller than f_s, and provides a fixed magnitude force that appears in a direction opposed to the motion. Its magnitude is independent on the velocity.

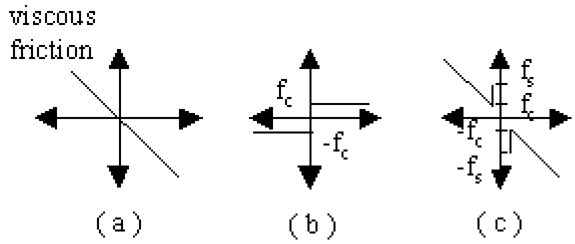


Fig. 1. a) Viscous friction characteristic, b) Coulomb friction characteristic, c) composed friction characteristic, illustrating static friction, Coulomb friction and viscous friction

Three regions that exhibit different linear models are v=0, v>0. The corresponding models are

$$V(t) = 0 \text{ , } v = 0 \text{ and } |f(t)| \leq fs \qquad (5)$$

$$f(t) = m * \ddot{x} + b * \dot{x} + fc \text{ , } \quad v > 0 \qquad (6)$$

$$f(t) = m * \ddot{x} + b * \dot{x} - fc \text{ , } \quad v < 0 \qquad (7)$$

According to Lewis &Yang [2], if the system is initially at rest and the magnitude of the applied force increases to exceed the breakaway value, the model will change from equation (5) to either equation (6) or (7) depending on whether the force is positive or negative. If the velocity at same point in time decreases in magnitude and declines to zero, the model will revert to equation (5) with dv/dt instantly forced to zero. The velocity may then remain to zero for some time, or the transition to the zero velocity model may precipitate another transition if the magnitude of f(t) exceeds the breakaway in the opposite direction. The velocity v will not change instantaneously because dv/dt must be finite. However, instantaneous changes in dv/dt will be observed when th nonlinear frictional components change instantaneously.

3.2 Pick up model

In order to determine the form error of a roundness standard, the pick up is the instrument used to give the correspondent linear displacement related to the error form of the roundness standard by contact with the same.

To improve the precision of an electronic pick up, a Kalman filter based study has been made to estimate the true position of the pick up.

Considering the movement equation of the pick up as:

$$J_a * \frac{d^2\theta}{dt^2} + B_a * \frac{d\theta}{dt} + k_a * \theta = F_a * l \qquad (8)$$

where:

J_a: Inertia of pick up arm
B_a: pick up viscous damping
K_a: pick up elastic constant
F_a: force that the pick up apply to the standard
L: length of the pick up arm,

and writing the pick up movement equation in the state space form:

$$\begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \dfrac{-K_a * l^2}{J_a} & \dfrac{-B_a * l^2}{J_a} \end{bmatrix} * \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{J_a} \end{bmatrix} * u \qquad (9)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} * \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}$$

The Kalman filter for discrete time corresponds to a sequence of propagations and updates, where the superscript "-" signal was adopted regarding the values during the propagation and the "^" signal for values immediately after updated.

The propagation cycle of the Kalman filter can be written as:

$$\bar{\theta}(k+1) = \Phi(k+1,k) * \hat{\theta}(k) \qquad (10)$$

$$\overline{Pk}(k+1) = \Phi(k+1,k) * \hat{P}k(k) * \Phi^T(k+1,k) + \Gamma(k) * Qk(k) * \Gamma^T(k) \qquad (11)$$

and for the update cycle

$$\hat{\theta}(k+1) = \bar{\theta}(k+1) + Gk(k+1) * [y(k+1) - Cd(k+1) * \bar{\theta}(k+1)] \qquad (12)$$

$$\hat{P}k(k+1) = \overline{P}k(k+1) - Gk(K+1) * Cd(k+1) * \overline{Pk}(k+1) \qquad (13)$$

$$Gk(k+1) = \overline{P}k(k+1) * Cd^T(k+1) * [Cd(k+1) * \overline{P}k(k+1) * Cd^T(k+1) + Rk(k+1)]^{-1} \qquad (14)$$

where:

Φ : state transition matrix associated to Eq. (9)
k+1 and k represent the moment in which the system is sampled
$\bar{\theta}$: the medium state
$\hat{\theta}$: the estimated state
$\overline{Pk}$: media of the state covariance
$\hat{P}k$: correspond to the state estimated covariance
Gk: Kalman gain
Cd: observation matrix asociated to Eq. (9)

The pick up simulation with Kalman filter has been performed adopting Qk=0.005*I and Rk=0.003 mm², where I corresponds to the identity matrix in order 2. Besides these parameters, a matrix gain was considered in the transition matrix to improve the response time.

4 SIMULATION RESULTS

The Kalman filter has been applied to feed a "Deadbeat" control that consider the nonlinearities caused by the static friction. Therefore, in order to prove the system functionality, a simulation considering altogether the Kalman filter, "Deadbeat" control and the static friction, was performed according to the diagram below.

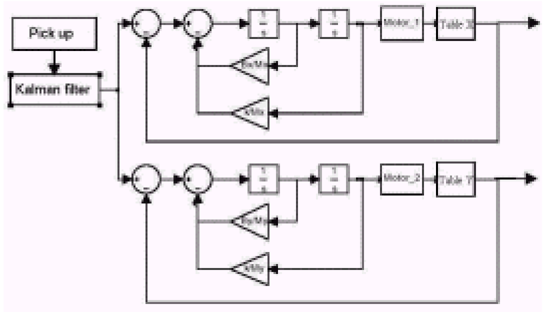
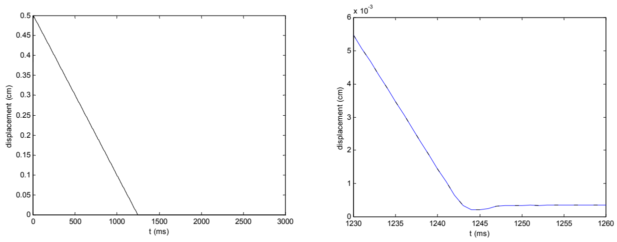


Fig. 2. Set simulation diagram

In the diagram, an electronic pick up which covers a roundness standard, generates signals that, after passing through the Kalman Filter, gives the positioning references to the XY table's controller and considers in its mathematical algorithm the nonlinearities due to the static friction of the table. The controlled table is moved by DC motors and has a positioning sensor for each translation axis that feeds back the system.

A computational simulation performing a deadbeat control system including the static friction and a Kalman filter that feeds the control in a saturated system limited in 2.5 V is showed below. For a maneuver from 0.5 cm to zero reference, we have for the superior table:



(a) (b)

Fig. 3. a) Displacement – computational simulation, b) zoom of the system stabilization zone

5. EXPERIMENTAL SIMULATION

In order to verify the results obtained by computational simulations, a study model has been built performing a closed loop "Deadbeat" control system.

The prototype was built using 24 VDC motor type to move a XY Table. This table has been built in stainless steel, with dovetail translation stage and a pinion rack movement system.

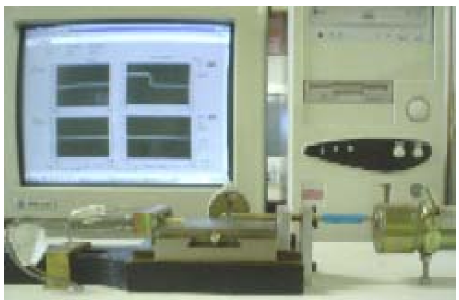


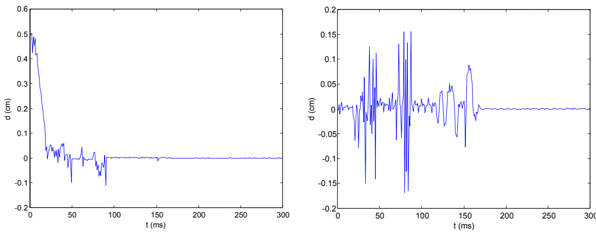
Fig. 4. Photo of the prototype

The experimental setup has been performed using a "PC 100 MHz" equipped with an AD/DA board and the control algorithm program made in "LabView" that communicates with the acquisition AD/DA board. The computer receives the positioning signal from the sensors connected to the XY Table. These signals are processed and converted to analog voltages through the AD/ DA board.

In view of the AD/ DA board concepts used in the prototype, which works in a range from –2,84 V to +2,84 V, construction of a signal amplifier was necessary to feed the motors that work with 24 VDC and 150 mA. For safety work a maximum voltage of 12 V has been used.

The whole experimental study has been performed in a study model, built in a simple way that does not feature all the details, but presents enough resources to attend and support the desired application. The whole project can be found in Lieu [4] .

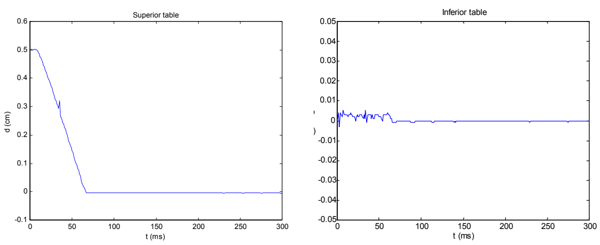
In a dynamic simulation performed in the prototype, a cycle of 300 sampling/second and period of 1 ms, the superior table initially situated at 0,5 cm must be driven to the zero reference while the inferior table remains stopped, aiming the verification of possible influences of the same to the movement of the superior table, in a simulation considering a saturation of 2.5 V in the AD/ DA board.



(a) (b)

Fig. 5. a) Displacement of the superior table, b) Displacement of the inferior table (both saturated in 2,5V)

In order to compare the system performance with low motor speed, the same simulation adopting a saturation of 1,5 V in the AD/ DA board was done.



(a) (b)

Fig. 6. a) Displacement of the superior table, b) Displacement of the inferior table (both saturated in 1,5V)

According to the graphics presented on figures (5) and (6) (Lieu [4]), we can note a significant reduction of noises during the positioning using low motor speeds. This reduces the vibration caused by the motors, mainly during the reversion of the motor rotation. The prototype simulation demonstrate that the system is able to position with a accuracy below 0,1 mm.

6. CONCLUSIONS

The main purpose of the present work is the design of a micropositioning table where through a closed loop based precise control, simulations of the system were made which results were confirmed by the construction of a prototype. This study model was able to prove the best control system to be applied in the micropositioning table.

In the numerical simulation of the "Deadbeat" control, the results achieved were close to the behavior of the experiments performed with the prototype, proving the efficiency of this method.

The use of precise displacement sensors like LVDT or encoders instead of the potentiometers, will certainly contribute for a better positioning accuracy.

When analyzing the prototype, possible external interferences as noises, mechanical adjustment and vibration caused by the motors, were detected and should be considered in other versions of the device.

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