Design and Development of Embedded System on ARM for On-line Characterization of DC Motor

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***Abstract*—An on-line characterization system has been developed for DC motors working in Micromanufacturing applications. These sensitive applications require high precision and high speed of response. The system has been programmed on ARM microcontroller, it actuates DC motor and automatically collects data while it is being accelerated and attains a steady speed ; the embedded routines process it instantly and returns the current values of inertia, friction coefficient, back-emf constant and torque constant. A prototype system for DC motor control has been developed in laboratory, it has been characterized and control experiments have been performed. when such Micromanufacturing applications progress in real-time, any change in the motor parameters, consequently in transfer function, can be found and utilized for better performance.**

***Keywords*-DC Motor Characterization; Embedded Characterization;**

I. Introduction

For a dc motor, charaterization implies finding constants of the equations of motion. Though, data-sheets are provided by manufacturers, but the parameters are bound to change for day to day operation, so attempt has been made to determine constants of a standard DC motor using an Embedded program. These requirements to evaluate parameters are necessary when the motor is to be employed in some operation where minute change in parameters will affect the performance. The progarm is employed for time-to- time evaluation of the sensitive parameters and feeding them to control system is important for better results in operations. The characterization module therefore can be i)run before every operation or ii) it can be invoked as an event when ever there is degraded performance or iii)as a background task far parameter monitoring and logging or iv) as periodic maintenace task for maintaing current record of parameters.This would provide good support to real-time control operations requiring high preceision, speed of response and fault tolerance. In Micromanufacturing applications there is growing demand for reliability of processes in real-time processcontrol along with Fault tolerance [1]. The system performance degrades due to parameter variations, plant disturbances and noise, the methods that deal with such problems fall under robust control, adaptive control, and intelligent control of DC motor systems. Control of dc motors using its nonlinear model is a difficult problem.

Despite their complexity, adaptive controllers have gained popularity due to their flexibility and robustness. Identification and control of electric motor drives using adaptive control schemes have been found effective, and satisfactory results have been obtained [2]-[8].

Besides motor dynamics being nonlinear, some of the motor parameters are state-dependent and time variant. The artificial neural networks (ANN's) based solution is applied to these nonlinear time-varying control problems [9]-[12].

The paper is organized as follows: Section-II describes modeling of DC motor system, section-III describes characterization hardware and software sub systems, section IV gives results of electrical and mechanical parameter evaluation, and finally discussion and conclusion of the work is presented.

II. DC Motor Modeling for Control

A parameter based representation of DC motor (Figure 1) driving an inertial load, shows the angular rate of the load, ω(t), as the output and applied voltage, v_{app} (t), as the input. Here, the magnetic field is assumed to be constant. The nomenclature used here are R is the resistance of the circuit, L is the self-inductance of the armature, i is the current through the coil, J is the moment of inertia of the load, K_m is the armature constant, K_b is the back-emf constant, $K_f(\omega)$ is a linear approximation for viscous friction, τ is the torque seen at the shaft of the motor, the differential equations that describe the behavior of this electromechanical system are stated below. The behavior of the motor can be described by the four equations stated below.

$$\tau\left(t\right) = K_m i\left(t\right) \quad (1)$$

$$J\dot{\omega}\left(t\right) = -K_f\omega\left(t\right) + K_m i\left(t\right) \quad (2)$$

$$v_{backemf}\left(t\right) = K_b\omega\left(t\right) \quad (3)$$

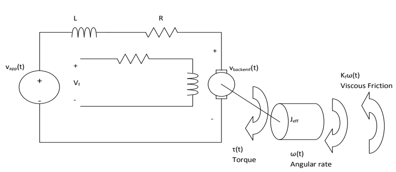

Figure 1. A parameter based representation of DC motor

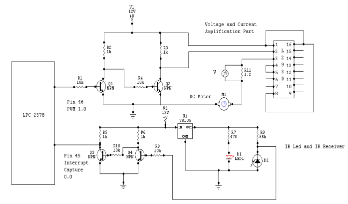

Figure 2. Schematic of Characterization Module

$$v_{app}\left(t\right) = L\frac{di\left(t\right)}{dt} + Ri\left(t\right) + v_{backemf}\left(t\right) \tag{4}$$

III. DC Motor Characterization System

A. Hardware Module

For characterizing dc motor, the motor is connected to ARM based microcontroller (NXP LPC 2378) through an interfacing circuit. Schematic of the arrangement is shown in Figure 2. To measure current through the motor, a resistance of 1.2 ohm is inserted in series with the motor. The Figure below (Figure 3 to 6) depicts the actual Characterization module.

B. Software Module

A constant PWM signal varying from 50% to 90% is applied from the microcontroller, amplified by Interfacing circuit and driving the motor to speeds 30 Hz to 100 Hz. A wheel with N=8 index holes is connected to the shaft. A pair of IR LED and Receiver is placed face to face in a fashion such that when an index hole comes in front of the LED, output of receiver goes low. Otherwise output of the receiver is high. The microcontroller counts the number of transition from high to low for a certain time interval and calculates speed (in Hz) of the motor from the relation. Speed = Time of counting $\times$ Number of Count / N. Once the speed has been calculated, acceleration is computed. Flow chart of DC motor characterization process is shown in Figure 7.Here all constants and coefficients are evaluated in S.I. unit system.

IV. Experimental Parameter Evaluation

In current development it has been assumed that the resistance and inductance of the system are not varying as the temperature and configuration changes are not dominant.

A. Measurement of Resistance and Inductance

Resistance and average inductance is measured directly with ohmmeter and LQR meter respectively, and it is found that Resistance = 6.4Ω and Inductance = 4.6$\times 10^{-3}$ H.

B. Measurement of back-EMF Constant

Expression for back-EMF Constant can be found by substituting steady state value di/dt = 0, in (4) as,

$$K_b = \frac{v_{app}(t) - Ri(t)}{\omega(t)} \tag{5}$$

To determine current through the coil a resistance of 1.2 $\omega\Omega$ is inserted into the current path of the motor and voltage across the resistance is measured, and the result is tabulated in Table 1 & 2. Average value is 6.16$\times 10^{-3}$.

C. Measurement of Motor Constant

Expression for Motor Constant is given by (1),

$$\tau\left(t\right) = K_m i\left(t\right)$$

Multiplying both sides by ω(t) gives

$$\tau\left(t\right) \times \omega(t) = K_m i\left(t\right) \times \omega(t) \tag{6}$$

At steady state, from energy balance formula it can be written that,

Input Power = Output Power

$$v_{app}(t) \times i(t) = \tau(t) \times \omega(t)$$

Comparing this with (6) yields,

$$v(t) \times i(t) = K_m \times \omega(t)$$

At steady state di/dt = 0 and (4) yields

$$i(t) = \frac{v_{app}(t) - K_b\omega(t)}{R} \tag{7}$$

Substituting i (t) in (5) and after simplification it becomes

$$K_m = K_b$$

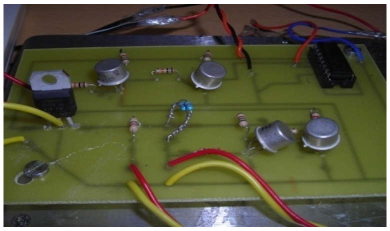

Figure 3. PCB of interfacing Circuit

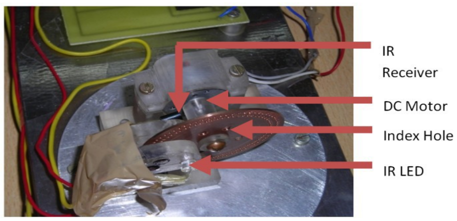

Figure 4. Motor and accessories for measuring Speed

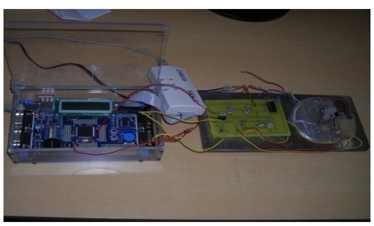

Figure 5. Complete Hardware Module

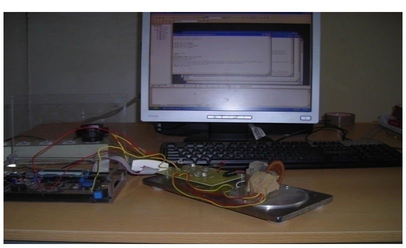

Figure 6. Hardware and Software Environment

D. Measurement of Inertia

Effective Inertia of the shaft and load is measured from motor side. Comparing (1) and (2) gives,

$$\tau(t) = J\dot{\omega}(t) + K_f\omega(t)$$

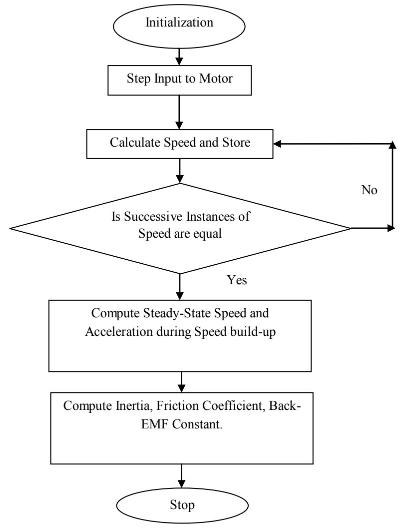

Figure 7. Characterization Process of DC motor

Table I
BACK-EMF CONSTANT

PWM (%)	Steady State Speed(Hz)	Voltage across 1.2Ω(V)	Current Through Motor (A)
12.5	32	0.035	0.029
25	65	0.079	0.066
37.5	97	0.13	0.108
40	111	0.145	0.121
50	125	0.221	0.184
62.5	149	0.319	0.266
75	160	0.446	0.372

Multiplying both sides by ω(t) yields,

$$\tau(t) \times \omega(t) = \{J\dot{\omega}(t) + K_f\omega(t)\} \times \omega(t) \quad (8)$$

Ignoring L term in (4) at steady speed gives ,

$$i(t) = \frac{v_{app}(t) - v_{backemf}(t)}{R} \quad (9)$$

And Energy balance Formula yields,

$$\tau(t) \times \omega(t) = v_{app}(t) \times i(t) - i^2(t) \times R \quad (10)$$

Now comparing (8) and (9) and substituting value i(t) from (9), and after some manipulation, expression for J is

Table II
BACK-EMF CONSTANT

Voltage Drop across Motor ≡ I×R(V)	Back EMF ≡V-IR(V)	Speed (radian/s)	K_b $\times 10^{-3}$(V·s)
0.22	1.33	201	6.68
0.5	2.58	408	6.32
0.82	3.77	609	6.19
0.92	3.98	697	5.7
1.4	4.71	785	6
2.02	5.6	939	5.96
2.83	6.31	1005	6.27

evaluated as [1]

$$J = \frac{v_{app}(t) \times K_b(\omega_2 - \omega_1)}{R \times \{(\dot{\omega}_1 \times \omega_2)\,(\dot{\omega}_2 \times \omega_1)\}} \tag{11}$$

Several experiments have been done to evaluate inertia with different PWM value. Table 3, 4& 5 shows results for 30% PWM which is shown graphically in figure 8. After evaluating for 12.5%, 25%, 37.5%, 40%, 50%, 62.5%, 75% PWM results have been averaged and it is found that J = 3.275026417×10^{-4} .

E. Measurement of Friction Coefficient

Expression for Friction Coefficient can be evaluated as follows. At steady state $\dot{\omega}$ = 0, using this condition in (2) gives,

$$\tau(t) = K_f\omega(t)$$

Multiplying this by ω(t) yields,

$$\tau(t) \times \omega(t) = K_f \times \omega^2(t) \tag{12}$$

And at steady state energy balance principle gives,

$$\tau(t) \times \omega(t) = v_{app}(t) \times i(t) - i^2(t) \times R \tag{13}$$

Comparison of (12) and (13) and some manipulation results expression for Friction Coefficient as,

$$K_f = \frac{v_{app} \times K_b}{R \times \omega} - \frac{K_b^2}{R} \tag{14}$$

Several experiments have been done to evaluate Friction Coefficient with different PWM value. Table 3, 4& 5shows results for 30% PWM and it is shown graphically in figure 9. After evaluating for 12.5%, 25%, 37.5%, 40%, 50%,62.5%, 75% PWM results have been averaged and it is found that K_f=1.42419433×10^{-6}.

[1] *suffices are quantites at respective time slots*

Table III
INERTIA AND COEFFICIENT OF FRICTION EVALUATED AT 30% PWM

Number of trial	1	2	3	4
$J\times10^{-4}$	2.821387	3.506485	3.419641	3.68269
$K_f\times10^{-6}$	1.458485	1.124193	1.458485	1.458485

Table IV
INERTIA AND COEFFICIENT OF FRICTION EVALUATED AT 30% PWM

Number of trial	5	6	7	8
$J\times10^{-4}$	3.274977	3.123156	3.471982	3.285066
$K_f\times10^{-6}$	1.371524	1.371524	1.371524	1.639756

V. CHARACTERIZATION RESULTS AND DISCUSSION

Several experiments have been performed to find all the coefficients. These coefficients have been used to evaluate transfer function. The First order and second order transfer functions have been evaluated from the basic four equation of a dc motor (section 2.0). First order modeling(inductance is ignored) shows very slow time response though practically it is not therefore this approximation is not suitable, hence second order transfer function is evaluated which is more close to practical case. First Order Transfer Function is given below; its step response from MATLAB is plotted in Figure 10.

$$\frac{\omega}{v}(s) = \frac{K_m}{R \times J \times s + (R \times K_f + K_m \times K_b)}$$

$$\Rightarrow \frac{\omega}{v}(s) = \frac{6150}{24890.2 \times s + 48.6464}$$

Second Order Transfer Function is given below; its step response from MATLAB is plotted in Figure 11.

$$\frac{\omega}{v}(s) = \frac{K_m/J \times L}{s^2 + \left(\frac{R}{L} + \frac{K_f}{J}\right) \times s + \frac{K_f \times R + K_m \times K_b}{J \times L}}$$

$$\frac{\omega}{v}(s) = \frac{6150}{1.508 \times s^2 + 24.94 \times s + 48.612}$$

It can be observed that dc gain for both type of modeling is equal but their time response is different. So, second order modeling is used for designing the controller.

VI. CONCLUSION

An embedded system has been developed on ARM microcontroller using second order model of DC motor system for electromechanical characterization of the motor. The

Table V
INERTIA AND COEFFICIENT OF FRICTION EVALUATED AT 30% PWM

Number of trial	9	10	11	12
$J\times10^{-4}$	3.129429	3.191879	2.940832	3.452793
$K_f\times10^{-6}$	1.371524	1.547862	1.458485	1.458485

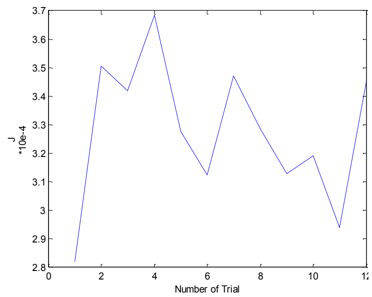

Figure 8. Inertia at 30% PWM

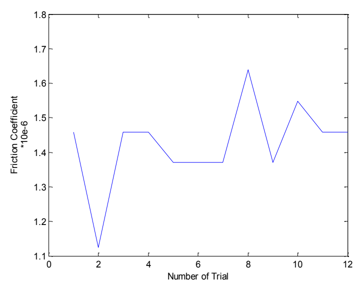

Figure 9. Friction coefficient at 30% PWM

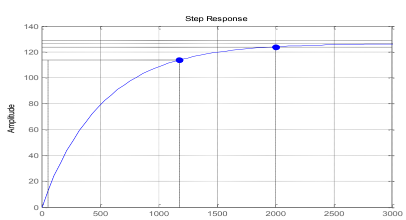

Figure 10. Step Response for first order Modeling

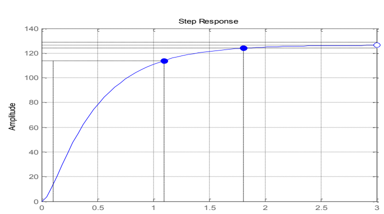

Figure 11. Step Response for second order Modeling

system's parameters of interest have been measured and monitored on-line which provide assistance to its control system in micromanufacturing operation to avoid any failure or degradation in performance. The values obtained in the systems for inertia, friction coefficient, resistance, inductance, Torque constant and Back-EMF Constant are 3.275026417×10^{-4} kg·m^2, 1.42419433×10^{-6} N·m·s, 7.6 ohm, 4.6 mH, 6.16×10^{-3} N·m/A and 6.16×10-3 V·s respectively.

The characterization module can be included as a real-time task in the program which can run as a periodic task to evaluate system parameters as a matter of routine checkup, alternatively, it can run as an event based task to check whenever control performance goes below certain level.

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