Simultaneous Sensing cum Actuating DC Motor

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***Abstract*—This work aims to develop a new measurement method to monitor the speed, velocity, and mechanical impedance of a DC motor platform without using conventional sensors. A back-drivable DC motor platform is developed which uses the motor as sensor cum actuator. The sensor cum actuator determines the mechanical impedance of the moving load. By calibrating the Transduction Matrix of the DC motor the angular velocity and torque load of the motor can be measured via measuring the motor's electrical impedance. The method is validated by measuring mechanical impedance of an out center linear spring that generates dynamically changing impedance.**

***Index Terms*—Sensor, Actuator, Electrical Motor, Monitoring, Measurement**

I. INTRODUCTION

As the end use devices, electric machines, consume around 70% of the total electric power in the world hence their significance for global energy and sustainability is a top priority. More interestingly, a vital indicator of economic health is the growth in production and use of electric machinery applications. Today, the use of electric machines have proceeded far beyond the traditional paradigm of their basic application in production-lines that grew exponentially 2-3 generations ago. As of now personal computers, portable disk drives, advanced permanent magnet servos, and piezoelectric haptic actuators have created a new paradigm for developing, designing, and using the electric machines. Novelties that still continuously take place in this field have led to innovations in medical equipment, wind generation, aircraft systems, and numerous other applications. That being said, condition monitoring of the electric machines has been of tremendous interest to the industry. Specially, researchers have looked and are still looking for cost-effective yet reliable monitoring solutions. This paper tries to propose a method to overcome this challenge in specific case of a DC electric machine.

Back to fundamentals of electric machines, an electrical motor is a device that converts electrical power into mechanical power. Considering a motor as a system, its electrical impedance determines how much electric power it consumes. Hence, monitoring impedance is important. Although there is substantial knowledge about electrical impedance, little is known about mechanical impedance. Similar to the electrical impedance which is defined by dividing the voltage over the current of the system, the mechanical impedance is defined by dividing the force by the velocity of the system.

Impedance control (i.e. mechanical impedance), proposed by Hogan [1], is usually employed in robotics and automatic manipulation of objects. The implementation of the control scheme requires installing force and velocity sensors. This adds to the intricacy and the finished cost of systems. The most common-place actuators are electrical motors but the working principle of other actuators like piezo-electric ones can be similar to motors to some extents. Anderson et al [2] proposed a method to measure the deformation of a piezoelectric-coated cantilever beam by means of electro-mechanical modeling of the piezoelectric actuator. The simultaneous actuation and sensing was able to effectively predict and control the oscillation of the cantilever beam. The drawback to the method was that the loading effectôs governing equation were needed to be solved to be decoupled.

Ling et al [3] were able to successfully remove the loading effect without solving the governing equations. Also, they provided dynamic measurement using simultaneous sensing and actuating, SSA. The method was successfully used for monitoring the micro drilling process by Ling et al in and monitoring mechanical impedance of human arm by Hondori et al in [4] all without using sensors. In these prices of work the transduction property of DC motors was used to achieve simultaneous actuation and sensing.

This paper presents a new approach for the motion monitoring and sensing of a DC motor platform where the electrical motor is used as an SSA unit. The work procedure is as follows:

1) Measuring electrical impedance by monitoring and correlating the electrical voltage and current;

2) Determining the mechanical impedance by means of electro-mechanical transduction; and

3) Validating the transduction matrix by testing known impedances

Section 2 of this paper discusses the methodology. Section 3 talks about obtaining the transduction matrix. Then Section 4, covers how to how to verify the method experimentally. Section 5, the final section, will wrap up the discussion and conclusion.

II. METHODOLOGY

A. What is mechanical impedance

For a rotary system impedance, z_m, at frequency equal to ω can relate torque, T, to angular velocity, $\dot{\theta}$ according to Equation (1) as follows:

$$T(\omega) = z_m(\omega) \times \dot{\theta}(\omega) \quad (1)$$

B. Transduction matrix

To measure mechanical impedance, one needs to measure the force and the velocity and calculate the ratio of them. Besides the traditional approach, [5]ï [7] have proposed using the transduction matrix to measure the impedance; Equation (2).

The idea is to make use of simultaneous sensing cum actuating (SSA) property of the electrical motors.

Figure 1 shows, an electric motor that is considered to have four poles: two inputs and two outputs.

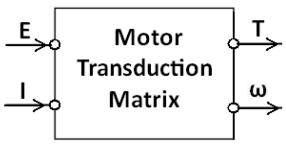

Figure 1: An electromechanical system as a four-pole block

The input and output are considered two vectors (each sized 2 by 1). E and i (i.e. voltage and current) are elements of the input vector whereas T and ω (i.e. torque and angular velocity) are elements of the output vector. The transfer function, relating the input and the output, is a two-by-two matrix which is called Transduction Matrix. As the name suggests, it transfers the electrical entries to the mechanical entries and vice versa.

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \times \begin{Bmatrix} T \\ \dot{\theta} \end{Bmatrix} \quad (2)$$

Using the transduction matrix, we measure the mechanical outputs based on measuring the electrical inputs as demonstrated in Equation (3). The transduction matrix can be obtained from motor specôs [8] or from a series of experiments [5].

$$\begin{Bmatrix} T \\ \dot{\theta} \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}^{-1} \times \begin{Bmatrix} E \\ i \end{Bmatrix} \quad (3)$$

Since $\dot{\theta}$ can reach zero that makes impedance nonsense, we first obtain the analytical signals, $\tilde{T}$ and $\tilde{\dot{\theta}}$ using Hilbert transform according to Equation (4). Then we introduce them to Equation (5). The mechanical impedance is obtained by dividing torque by angular velocity; Equation (5) [4], [9].

$$\begin{aligned} \tilde{\dot{\theta}} &= \dot{\theta} + j(Hilbert(\dot{\theta})) \\ \tilde{T} &= T + j(Hilbert(T)) \end{aligned} \quad (4)$$

$$z_m = \frac{\tilde{T}}{\tilde{\dot{\theta}}} \quad (5)$$

III. OBTAINING THE TRANSDUCTION MATRIX

A. Derivation of the Transduction Matrix in Steady State Condition

When the effect of steady state is considered only, the energy flow in and out of the DC motor can be modeled as shown in Figure 2. The input and output are the electrical power (P_e), and the mechanical power (P_m) respectively. The power loss (P_l) should also be considered due to the internal resistant (R) of the DC motor. Hence, the power equivalence can be expressed as follows: [8]

$$P_e = P_m + P_l \quad (6)$$

or

$$E \cdot i = T_m \cdot \omega + i^2 \cdot R \quad (7)$$

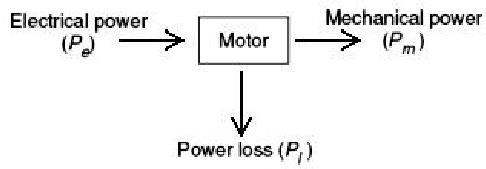

Figure 2: Input and output of motor [7]

The torque of motor is proportional to current [7]:

$$T_m = K_T \cdot i \quad (7)$$

K_T is a torque constant which is experimentally determined. To derive the electro-mechanical transduction matrix when the DC motor runs on steady state, Equations (7):

$$E = \frac{T_m \times \omega}{i} + i \times R \quad (8)$$

Also the current is related to torque based on the following equation:

$$i = \frac{T_m}{K_T} \quad (9)$$

Introducing Equation (9) into Equation (8) gives:

$$E = K_T \times \omega + \frac{R}{K_T} \times T_m \quad (10)$$

Now Equations (9) and Equation (10) can form a matrix equation as follow:

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \left[T_{ij}\right] \times \begin{Bmatrix} -T_m \\ \omega \end{Bmatrix} \quad (11)$$

Note that T_m carries the minus sign because by definition the mechanical port applies the torque to the transducer. From the load point of view the sign will be positive. Finally, the derived transduction matrix is given by:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} -\dfrac{R}{K_T} & K_T \\ -\dfrac{1}{K_T} & 0 \end{bmatrix} \quad (12)$$

B. Transient state derivation

Based on a block diagram for a DC motor and an equivalent circuit, the transduction matrix in transient-state can be derived. The equivalent circuit is shown in Figure 3 and the block diagram is shown in Figure 4. The governing equations for electrical and mechanical ports of the DC motor are expressed as follow: (According to Kirchhoff and Newton laws [10])

$$E = i \times R + L\frac{dI}{dt} - E_{emf} \qquad (13)$$

$$T_m = T_f + T_l + J\frac{d\omega}{dt} - B \times \omega \qquad (14)$$

In The above equations i is current, R and L are the equivalent resistance of the motor respectively; E is voltage; T_f is torque due to friction; T_l is loading torque; J is moment of inertia; B is damping coefficient; and t is time.

Furthermore, the motorĝs torque and the back electromotive force (back-EMF) voltage are proportional to the current and rotating speed of the motor, respectively: [10]

$$V_{emf} = K_E \cdot \omega \qquad (15)$$

K_E is the voltage constant of the DC motor.

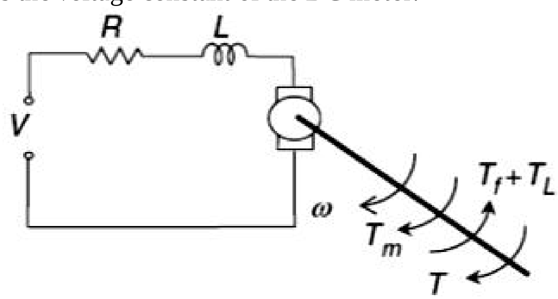

Figure 3: Equivalent circuit of DC motor [10]

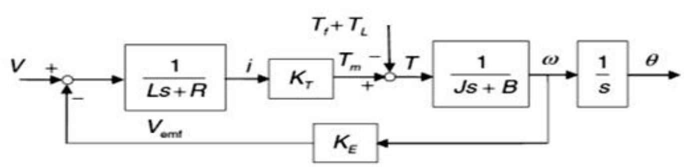

Figure 4: Block diagram of an equivalent DC motor [10]

The electro-mechanical transduction of a DC motor in a transient state can be derived considering the block diagram of the equivalent circuit shown in Figure 4.

The derivation of component T_{11} in the transduction matrix is illustrated as follows. Based on the definition of T_{11} which is $T_{11} = E/T_m\big|_{\omega=0}$; the condition $\omega = 0$ will lead to $V_{emf} = 0$. Hence, torque T_m will be defined as follows $T_m = E/L \times s + R \times K_T$. Finally, this component will be $T_{11} = E/T_m\big|_{\omega=0} = -L \times f + R/K_T$.

All the other three components will be derived in the same way and the final transduction matrix is as follows:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} -\dfrac{L \times f + R}{K_T} & K_E \\ -\dfrac{1}{K_T} & 0 \end{bmatrix} \qquad (16)$$

In order to investigate the relationship between transient states and steady state conditions the following items are checked:

If the determinant of transduction matrix is equal to 1, according to Equation (17):

$$det([\,T_{ij}\,]) = 1 \text{ (steady and transient states)} \qquad (17)$$

The component T_{11} in matrixes of both states should be the same under the condition $L \approx 0$ (this condition is actually an approximation).

The component T_{12} (K_T vs. K_E): The electrical and mechanical powers of a DC motor are supposed to be equal under the assumption that the DC motor is an ideal power converter. Hence the power is:

$$P_{motor} = V_{emf} \cdot i = T_m \cdot \omega \qquad (18)$$

Introducing Equation (9) and Equation 13) into Equation (18) gives:

$$K_E = K_T \qquad (19)$$

T_{12} in Equation (12) and Equation (13) are the same. When condition $L \approx 0$ is met, transduction matrices in steady state and transient state are identical. The DC motor used in this research is an AEROTECH-1035, the specifications of the DC motor selected are shown in Table 1. Also the equivalent circuit components are shown in Table 2. Based on these values, the transduction matrix is shown in Equation (20).

Table 1: Mechanical specifications of the DC motor

Max voltage	Max Current	Max peed
40 V	4.1 A	6000 rpm

Stall torque	Peak torque	Output power	Weight
0.25 N.m	1.84 N.m	129 W	1.6 Kg

Table 2: Electrical Parameters of the DC motor

Torque constant, KT, (N-m/A)	Resistance, R (Ohm)	Armature Moment of Inertia (kg-m2)
0.06	0.9	3.8x10-5

Back-EMF constant, KE (V /KRPM)	Armature Inductance (mH)
6.3	2.0

$$[T_{ij}]_{Motor} = \begin{bmatrix} -15 & 0.06 \\ -16.667 & 0 \end{bmatrix} \begin{pmatrix} \dfrac{\text{Volt}}{(\text{N.m})} & \dfrac{\text{Volt}}{(\text{rad/sec})} \\ \dfrac{\text{A}}{(\text{N.m})} & \dfrac{\text{A}}{(\text{rad/sec})} \end{pmatrix} \qquad (20)$$

IV. EXPERIMENTAL VERIFICATION OF THE METHOD

For the motor driven mechanism a low impedance DC motor together with a low ratio gearbox are chosen; the impedance of this mechanism is low enough to be back-drivable so as to make sure that the loadĝs effect is transmitted to the motor that, here, acts as an actuator/sensors. The setup also involves a current and a voltage sensors, and a data acquisition system.

A. Method justification

The mechanical impedance that was obtained in the previous section, is challenged by measuring the impedance of an object with a known mechanical impedance. A linear spring is attached eccentrically to the rotating wheel and as the wheel rotates the impedance is measured; the tensile force of the spring generates mechanical impedance that can be measured and compared against the analytical prediction..

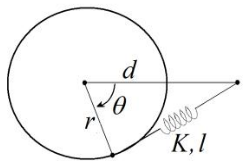

Figure 5: Shoulder wheel with the spring attached to it

Figure 5 shows the spring which is attached eccentrically to the shoulder wheel; when the wheel rotates, the springôs length changes and it produces a pulling force on the wheel.

Depending on θ, the springôs pulling force can either accelerate or decelerate the motion. It results in a resistance to the CCW motion when $0<\theta<180$. While after 180 degree, when $180<\theta<360$, it accelerates the motion. There might exist both resistive and assistive forces in different postures. The springôs response during motion is a force with its tangential component affecting the motion. Figure 6 shows the configuration of the force and moment arm when $0<\theta<90$.

The moment caused by force F at the centre, O, generates mechanical impedance at the rotating wheel. The impedance can be obtained from dividing F by the speed at point B. Based on mathematical and mechanical calculations the mechanical impedance of the wheel, z_m can be predicted by Equation (21).

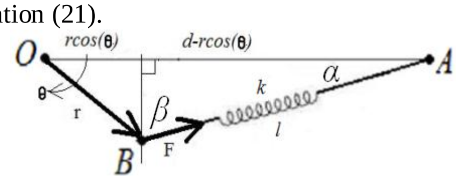

Figure 6: Spring force acting on the wheel

$$z_m = rk\left(\sqrt{r^2+d^2-2rd\cos\theta}-l_0\right)\times\ldots \quad \frac{d}{\omega\sqrt{r^2+d^2-2rd\cos\theta}}\sin\theta \qquad (21)$$

All constant values such as r, d, and l_0 are measured from the experimental setup and are equal to 2.7 cm, 11 cm, and 8 cm respectively. Spring stiffness, k in by adding mass, measuring displacement of the spring and then using least squares fitting to ñ$F=k.x$ò. The stiffness was found to be 98.75 N/m. The resultant z_m is calculated by Matlab® and shown in Figure 7.

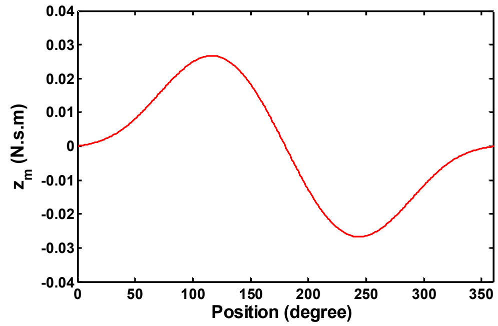

Figure 7: Analytical results showing mechanical impedance of the spring on the wheel [6]

Also based on transduction matrix of the motor-gearbox-wheel system, mechanical impedance was measured in an experiment when the spring is attached to the shoulder wheel. In Figure 8 data from the experiment can be seen. If error is defined as the discrepancy between theoretical and experimental results, the root mean squared error is equal to 0.0015. The reason that maximum error occurs between position $\theta = 0$ to 25^o is that the method is less accurate when the torque produced by the spring force is changed from negative to positive. Such change happens at $\theta = 0$ according to Figure 8.

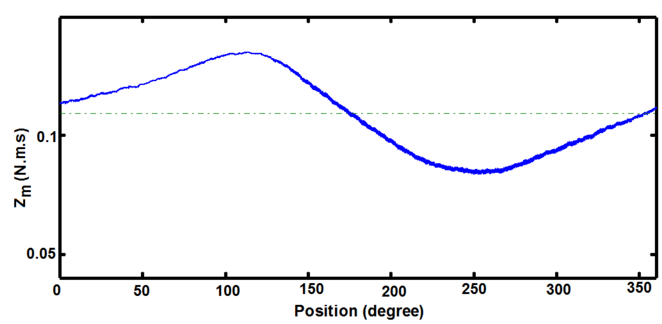

Figure 8: Experimental result (solid blue) of mechanical impedance

The agreement between measured value and analytical solution supports and validates the accuracy of the measurement method. Now the method is prepared to be used for monitoring the mechanical impedance of the load and monitoring the condition of the motor while operating.

V. Disscussion and Conclusion

The Transduction Matrix concept was applied to a DC electric machine; the matrix enabled us to measure the torque and angular velocity of the motor in order to measure the mechanical impedance even though no sensor for measuring the mechanical values were used. Instead, the transduction matrix took in the voltage and current and applied the matrix to obtain torque and angular velocity. A thorough experimental procedure was then performed to verify the soundness of the transduction matrix defined. A mechanical component with a known mechanical impedance was examined by the transduction matrix. The component selected was a linear spring that were attached to the system so as to generate a time variant mechanical impedance. The system proved functional in measuring the mechanical impedance and tracking its changes.

For future work, miniaturization of the voltage and current sensors is the most important thing to do. Also using small A/D signal acquisition devices that connect to cell phones, we will be able to transmit the data to a smart phone; using smart phone apps (i.e. Andoird or iPhone), we will be able to develop online monitoring systems. The comprehensive goal of this work is to contribute to the field of biomedical engineering to create a sensorless method for monitoring the movement functions of people undergoing physical therapy; good examples of the application can be found in haptic [11], [12] physical therapy and rehabilitation.

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