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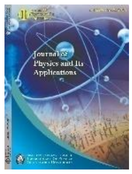

Transduction matrix to enable sensor-less application of DC motor

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A B S T R A C T

One of the methods to achieve sensor-less application of a motor is transduction matrix method. Transduction matrix is a 2x2 matrix that show the relationship between electrical port and mechanical port of the motor. The mechanical output of the motor can be calculated from its electrical input with the help of transduction matrix and it reduces the need for mechanical sensor. In this paper, transduction matrix of a chosen DC motor is obtained by calculating a set measurement data of its mechanical and electrical port with help of least square method. The calculated mechanical output from the matrix show less than 5% error from the measured one This proves that the transduction matrix method is able to predict mechanical output of the DC motor accurately.

1. Introduction

Nowadays, sensor development is in the direction of size reduction. This development makes sensor installation will have less or none effect to the system. One example of sensor development is the development of sensor-less position control of a brushless DC motor [1,2]. The aim of this sensor-less method is to replace the usage of bulky mechanical sensor such as encoder with simple electrical sensor. This development will help in reduce cost and weight to the system. It will also help in increase the reliability of the system because most of the system failure is due to mechanical sensor failure.

Most of this sensor-less method, make use mathematical modeling and algorithm to predict the rotor position [3–5]. The motor is modeled as a simple circuit and the rotor position is calculated from the emf-voltage. Similar concept with sensor-less detection of brushless DC motor, we develop transduction matrix method to model electromagnetic actuator. This method will allow the measurement of the mechanical quantities of electromagnetic actuator from its input electrical [6–10].

This transduction matrix is a 2x2 matrix that model the relationship of electrical input and mechanical output of an electromagnetic actuator. The transduction matrix is based on theory of transfer matrix, also known as two-port network and four poles parameter method. The electromagnetic actuator is model as two port network consist of two ports (electrical input port and mechanical output ports) with each port have two poles. Transduction matrix shows the relation between one input pole with one output pole that is independent to the others.

One example of electromagnetic actuator is DC motor. The motor consists of coil of wire and a permanent magnet. When voltage (E) is applied to the coil, the current (i) will flow in the coil and generate electromagnetic field. This electromagnetic field will attract the permanent magnet attached to the motor shaft and turn a motor shaft into certain rotation speed (Ω_m) and torque (T_m) to generate mechanical motion. This relation between voltage, current, torque and rotation speed at the motor can be relate and model with the transduction matrix. By knowing the transduction matrix of a DC motor, we can make use of the transduction matrix to calculate torque and rotation speed of DC motor thru its voltage and current. Thus, the torque and rotation speed sensor can be replaced with a small size current and voltage sensor in sensing the mechanical system that is attached to the motor.

This paper will introduce the method to obtain the transduction matrix of DC motor. First, it will show the model of DC motor in form of transduction matrix and mathematical formulation to obtain the matrix. After that, an experimental setup is designed to obtain the required set of data in obtaining the matrix. Last the calculated result and measured result of the motor's mechanical quantities are compared to show the accuracy of the method.

2. Transduction matrix of DC motor

A DC motor, similar with other electromagnetic actuator, can be modeled as a two ports, four poles networks. The ports are electrical port and mechanical port. Each port has two poles. In the electrical port, the two poles are voltage (E) and current (i). The two poles of mechanical port are torque (T_m) and rotation speed (Ω_m). The relation between all the fours poles can be relate with the transduction matrix ([t]) as shown in Figure 1.

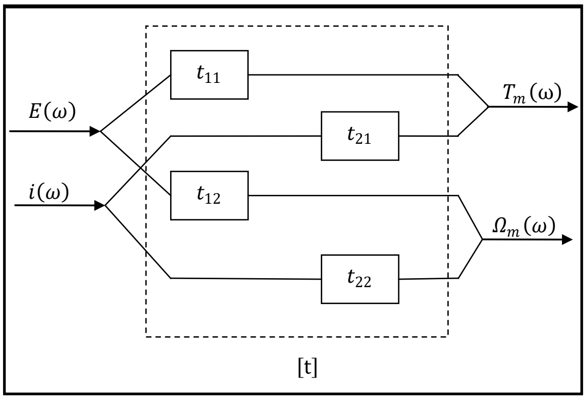

Fig. 1: A 2 ports, 4 poles model of DC motor

Figure 1 shows that there are four elements of the matrix to show the relation between electrical port and mechanical port. Each element relates one pole of electrical port with one pole of mechanical port that is independent from the other poles. Those elements can be categorized into two boundary condition and formed into 2x2 matrix. The boundary conditions are free condition (Ω_m = 0) and clamped condition (T_m = 0). The matrix is what we called transduction matrix and is written as :

$$\begin{Bmatrix} E(\omega) \\ i(\omega) \end{Bmatrix} = \begin{bmatrix} t_{11}(\omega) & t_{12}(\omega) \\ t_{21}(\omega) & t_{22}(\omega) \end{bmatrix} \begin{Bmatrix} T_m(\omega) \\ \Omega_m(\omega) \end{Bmatrix} \tag{1}$$

where

$t_{11} = \frac{E(\omega)}{T_m(\omega)}\Big| \Omega_m(\omega) = 0$, $t_{12} = \frac{E(\omega)}{\Omega_m(\omega)}\Big| T_m(\omega) = 0$,
$t_{21} = \frac{i(\omega)}{T_m(\omega)}\Big| \Omega_m(\omega) = 0$,and
$t_{22} = \frac{i(\omega)}{\Omega_m(\omega)}\Big| T_m(\omega) = 0$

If we are interested to calculate the mechanical output of a DC motor from its electrical input, equation (1) can be modified by taking the inverse of transduction matrix and multiply into equation, hence:

$$\begin{Bmatrix} T_m(\omega) \\ \Omega_m(\omega) \end{Bmatrix} = \begin{bmatrix} t_{11}(\omega) & t_{12}(\omega) \\ t_{21}(\omega) & t_{22}(\omega) \end{bmatrix}^{-1} \begin{Bmatrix} E(\omega) \\ i(\omega) \end{Bmatrix} \tag{2}$$

Transduction matrix of DC motor can be obtained with two methods which are mathematical modeling and experimental measurement. Mathematical modeling makes use of equivalent circuit of DC motor to calculate the transduction matrix. Experiment measurement makes use of a set measured data of input and output of DC motor. The data are used to obtain the matrix. This next section will explain both methods.

2.1. Mathematical modeling of DC motor

A DC motor can be modeled as an equivalent circuit that consist of inductance (L), resistance (R) and voltage source (E_{emf}) in series as shown in Figure 2. Due to the voltage (E) applied to the circuit, current (i) flow in the circuit. This current is linearly related with the torque generate at the motor. The generated torque will be used to overcome inertia of motor (J_{motor}), friction torque (T_f) and loading torque (T_L). Based on that, relationship at electrical part of the motor can be written as:

$$E = iR + L\frac{di}{dt} + E_{emf} \tag{3}$$

and the relationship of the mechanical part of the motor as :

$$T_m = J_{motor}\frac{d\Omega_m}{dt} + T_f + T_L \tag{4}$$

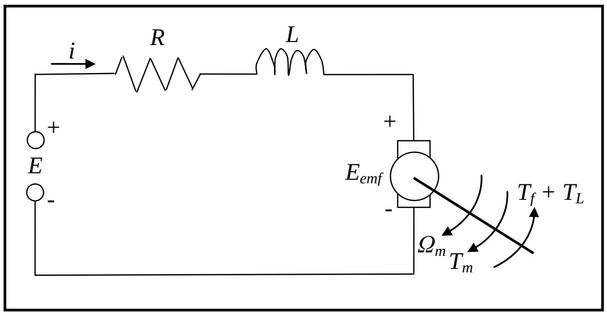

Fig. 2: Equivalent circuit of DC motor

In DC motor, there are motor constant that is a function of magnet's dimension inside the motor, motor winding and generated magnetic field. These motor constants linearly relate the motor current (i) with torque produced by the motor (T_m), that is called k_T and back emg voltage (E_{emf}) with rotational speed of the motor (Ω_m), that is called k_E. With those motor constants, equation (3) and equation (4) can be linked together and by taking Laplace transform, a block diagram in Figure 3 is formed.

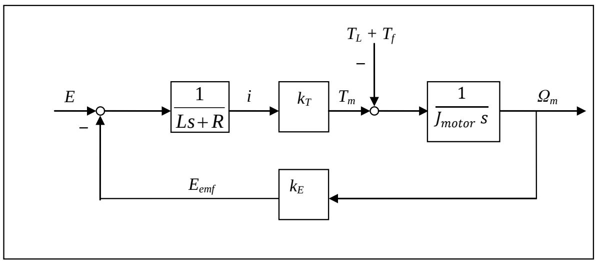

Fig. 3: Block diagram of DC motor

Transduction matrix of a DC motor can be obtained by applying the boundary conditions (Ω_m = 0 and T_m = 0) to the block diagram and solve each element based on equation (1). The transduction matrix that is obtained are:

$$[t] = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \begin{bmatrix} \frac{Ls+R}{k_T} & k_E \\ \frac{1}{k_T} & 0 \end{bmatrix} \tag{5}$$

Equation (5) shows element of transduction matrix of a DC motor. Each element is a function of the motor properties. Hence, transduction matrix itself is the function of the motor properties. Normally, those motor properties are calibrated by the manufacturer and given in the motor catalog. Thus, transduction matrix of a given motor can be obtained straight away from the motor catalog.

2.2 Experimental measurement to calculate transduction matrix

In experimental method to obtain transduction matrix, it is not advisable to apply boundary conditions (Ω_m = 0 and T_m = 0). The boundary conditions are hard to achieve and can cause damage to motor itself. The other approach to obtain the transduction matrix is thru a set of experiment data and linear regression method. This method makes use the assumption of linearity and independency of each element of the matrix. If we have a set data of electrical port (E_1,i_1,E_2,i_2,...,E_n,i_n) and mechanical port (T_{m1}, Ω_{m1}, T_{m2}, Ω_{m2},..., T_{mn}, Ω_{mn}) of a chosen DC motor, based on equation (1), the transduction matrix will relate linearly between the set data, which can be written as :

$$[Elec] = [t][Mech] \quad (6)$$

To obtain the transduction matrix, the equation can be rewritten based on least square formula as:

$$[t] = ([Mech]^t[Mech])^{-1}[Mech]^t[Elec] \quad (7)$$

where :

$$[Elec] = \begin{bmatrix} E_1 & E_2 & \dots & E_n \\ i_1 & i_2 & \dots & i_n \end{bmatrix}$$

and

$$[Mech] = \begin{bmatrix} T_{m1} & T_{m2} & \dots & T_{mn} \\ \Omega_{m1} & \Omega_{m2} & \dots & \Omega_{mn} \end{bmatrix}$$

Equation (7) is the formula to obtain transduction matrix with a set of measurement data. Transduction matrix of a chosen motor can be obtained by obtaining a data set of its mechanical port and electrical port. The setup of the experiment to obtain the measured will be explained in the next section.

3. Experimental setup to obtain transduction matrix

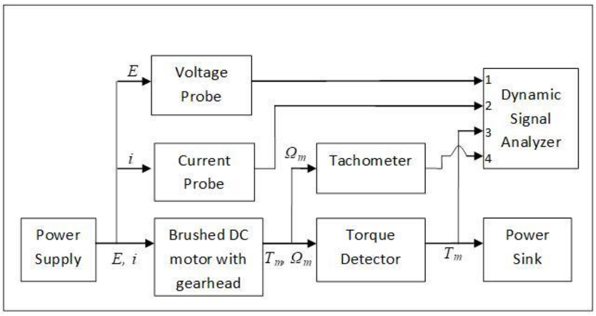

Fig. 4: Experimental setup

The experimental setup to obtain transduction matrix of a chosen motor are show in Figure 4. The setup consists of dynamic signal analyzer to acquire and store the signal from several sensors. The sensors that are connected to dynamic signal analyzer are torque detector to measure torque of the motor, tachometer to measure rotation speed of the motor, voltage probe to measure the voltage given to the motor, and current probe to measure current drawn by electric motor. A power sink is attached to the end of torque detector, which is couple with the chosen motor. The purpose of the power sink is to give loading to the motor.

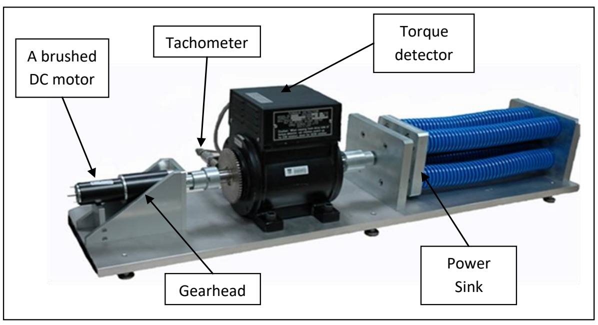

Fig. 5: Power sink

Figure 5 show the design of power sink. The power sink is designed with purpose to give an incremental load of power sink. It consists of a lead screw, a moving platform that is attached to the nut and four compression springs. The platform is linked with the springs. When the lead screw is turned by the motor, it will move the platform to compress the spring. Due to linear relationship in spring, the further the platform compress the spring, the higher load resistance in the spring. Hence, the torque required to compress the spring is higher as well.

The experiment is done by applying voltage to run the motor. The motor will turn torque detector and power sink. Due to the turning, the plate at power sink will move and compress the spring. Thus, the motor will experience an incremental torque. This torque, rotation speed, voltage and current at the motor are recorder with their respective sensors. The results are sampled and recorded using dynamic signal analyzer with sampling frequency of 2000 Hz and period of 8 seconds. Hence, we have 16,000 data sets of torque, rotation speed, voltage and current of motor.

4. Obtaining transduction matrix of a chosen DC motor

A chosen DC motor with a planetary gearhead is used in this experiment. The motor is Maxon motor RE40 with its planetary gearhead. The parameter of the motor, as given by the catalog, are :

a) Motor Power : 150 Watt
b) Nominal Voltage : 24 Volt
c) Gear reduction : 353 : 1
d) Max efficienct : 68%
e) Resistance : 0.317 ohm
f) Inductance : 0.0823 mH
g) torque constant with the gear : 7.2488 nm/A
h) Speed constant with the gear : 10.634 V/rad

By substituting these parameter to equation (5), we obtain the transduction matrix of the chosen motor to be

$$[t] = \begin{bmatrix} 0.0446 & 10.634 \\ 0.138 & 0 \end{bmatrix} \quad (8)$$

which is called theoretical transduction matrix because the matrix is obtained with theoretical derivation of the DC motor.

Transduction matrix thru experimental method is obtained with equation (7) and a set data of torque, rotation speed, voltage and current of the chosen motor. The set data is obtained with experimental setup mention above. The experiment is conducted by turning the DC motor on for 8 seconds. The mechanical and electrical data of the DC motor are acquired and plotted in Figure 6. By substituting the data into equation (6), transduction matrix of the motor is calculated as :

$$[t] = \begin{bmatrix} 0.0566 & 10.4075 \\ 0.1419 & 0,1109 \end{bmatrix} \quad (9)$$

which is called experimental transduction matrix because the matrix is obtained with experimental measurement. By obtaining the transduction matrix, torque and rotation speed of chosen motor can be calculated from its electrical input with the help of equation (2).

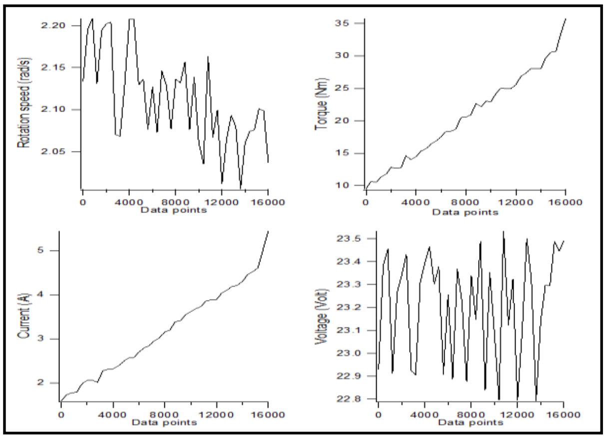

Fig. 6: Measurement result of electrical and mechanical port of a chosen DC motor

Comparing transduction matrix from equation (8) and equation (9), we observe that there is a big difference in t_{22} of both transduction matrix. In equation (8), there is no value for t_{22}. This means our motor model assume that there is no relationship between current of the motor (i) with rotation speed of the motor (Ω_m). However, transduction matrix at equation (9) shows otherwise. The rotation speed affect the current of the motor.

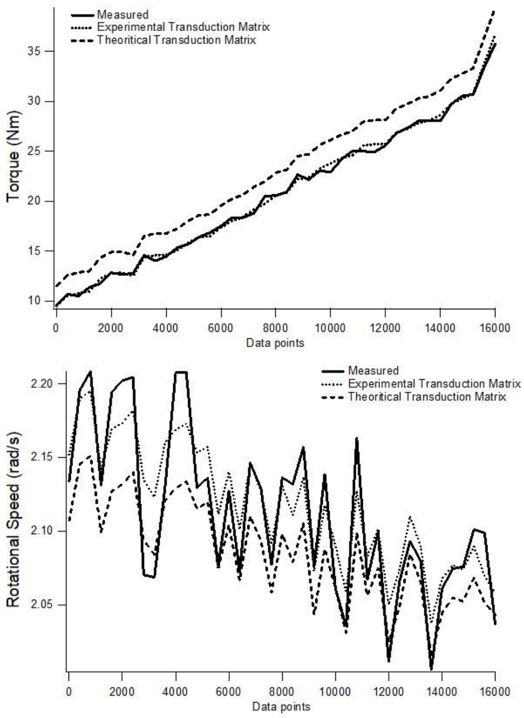

Fig. 7: Torque and rotation speed obtained from both transduction matrix and measurement

In order to compare the accuracy of both the transduction matrix, we substitute the data set of voltage and current and the transduction matrix's result to equation (2). Figure 7 shows both the results for torque and rotation speed and the comparison with measured torque and rotation speed. The result shows that experimental transduction matrix predict torque and rotational speed of the motor quite closed with the measured one compare to theoretical one.

Figure 8 and Figure 9 show absolute error of torque and rotation speed calculated from transduction matrix with respect to measured one.

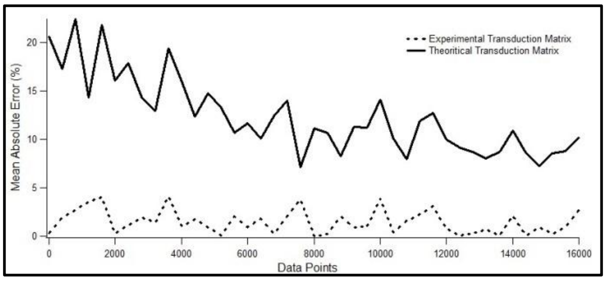

Fig. 8: Absolue error of torque from transduction matrix with respect to measured torque

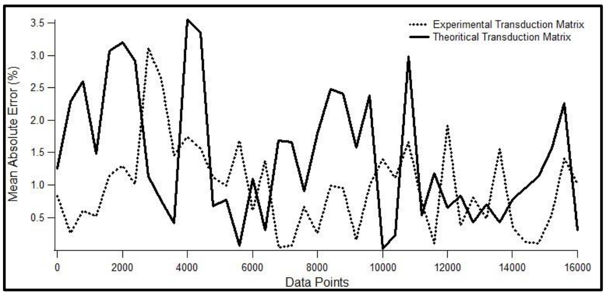

Fig. 9: Absolute error of rotation speed from transduction matrix with respect to measured rotation speed

Figure 8 shows that torque obtain from experimental transduction matrix have maximum error of 5% with RMS error 1.92%, whereas torque obtain from theoretical transduction matrix have an maximum error of 22% with RMS error 13%. Figure 9 shows maximum error of rotation speed obtain from experimental transduction matrix is 3.11% with RMS error 1.18%. Maximum error of rotation speed obtain from theoretical transduction matrix is 3.55% with RMS error 1,74%. Based on those results, we can conclude experimental transduction matrix predict mechanical output of DC motor accurately with absolute error less than 5%.

5. Conclusion

Transduction matrix is one of the methods to model the relationship between electrical input and mechanical output of the actuator. Element of the matrix is a properties of the actuator itself and its values is assumed to be constant along time. Obtaining transduction matrix of an actuator will allow us to measure mechanical quantities of electromagnetic actuator thru its electrical input. In order to obtain the matrix, a set data of measured voltage, current, torque, and rotation speed of the chosen motor are needed. Transduction matrix of the motor can be obtained with the help of equation (7).

In our experiment of obtaining transduction matrix of an actuator, a chosen DC motor is measured to obtain its transduction matrix. The mechanical quantities of the motor can be calculated with the help of the matrix. The result shows that the calculated result have maximum 5% difference from the measured one. Thus, with this method a DC motor can become a self sensing actuator. After obtaining its transduction matrix, the motor can be used to simultaneously actuate a system and sense the mechanical quantities of the system, example in the apllication the DC motor can be used to turn a bolted joint and measure the tightness of the joint.

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