A quasi-static modelling approach of electromechanical actuators

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Abstract

This paper presents a suggested modelling approach of an electromechanical actuator, where the performance of involved semiconductor devices and tentative motors as PM, transversal, torus, and switched reluctance electrical machines are condensed into look-up tables. Current and voltages are then described in form of quasi-static rms values quantities, and the actuator mechanical outputs in momentary forces and velocities. The proposed modelling approach is considered to be one ingredient in future build-up of models of entire MEA aircrafts.

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Design of the electric power systems of a More Electric Aircraft (MEA) comprises dimensioning of several electromechanical actuator systems. During flight the effective mechanical outputs of the actuators vary considerably slower than the voltages and currents in the corresponding electrical machines and semiconductor devices. To facilitate modelling of the whole system and decrease simulation time it is feasible to separate the high and low frequency behaviour of these components [1]. According to a general electromagnetic transducer model [2] equation (1) relates the terminal voltage and current to the force and velocity of an actuator when the periphery speed v is related to the angular speed according to $v = r_1\omega$ and the output torque is $\tau = r_2F$.

$$\mathcal{E} = z_e I + r_1 T_{em} v \quad (1a)$$

$$\tau = r_2 T_{me} I + r_2 z_m v \quad (1b)$$

For a general transducer $T_{em} = T_{me} = B_0 l$, where B_0 is the effective magnetic flux density and l is the effective length of the winding wire subjected to B_0 . The fundamental feeding angular frequency ω_e is assumed to be considerably higher than the mechanical angular frequencies. This means that one can regard time varying rms values of voltages and currents on the electrical side

and related time varying torque and angular values on the mechanical side. The torque and counter EMF constants are $t = r_2 T_{me}$ and $e = r_1 T_{me}$, respectively, and are normally specified by the electrical machine producer. An equivalent circuit can now be drawn according to Fig. 1.

Fig. 1. Equivalent circuit of an electromagnetic actuator connected to an electric and mechanical circuitry represented by the voltage and torque sources U and τ_L , respectively.

A corresponding expression of the electromechanical efficiency also can be defined according to

$$\eta = \frac{P_{mech}}{P_{electric}} = \frac{tI\omega}{tI\omega + r_e I^2} \Rightarrow r_e = \frac{1-\eta}{\eta} t \frac{\omega}{I}$$

Kirchhoff's voltage law then gives

$$U - e\omega = I r_e$$

$$tI = J \frac{d\omega}{dt} + \tau_L$$

With efficiency values in form of look-up tables the resulting equation system of the model is

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$$U - e\omega = \frac{1 - \eta(\omega, \tau)}{\eta(\omega, \tau)} t\omega \quad (2a)$$

$$tI = J \frac{d\omega}{dt} + \tau_L \quad (2b)$$

$$\tau = tI \quad (2c)$$

$$\eta = \eta(\omega, \tau) \quad (2d)$$

A common mode of operation of an electric actuator is when it is loaded mechanically by an inertial mass and an equivalent viscous load and fed by a Pulse Width Modulated voltage source. This situation corresponds to an effective rms current through the actuator. The actuator then is described by J , e , t , and by its efficiency function $\eta(\omega, \tau)$.

A computational fast approach is to prescribe this current variation. This yields only one differential equation to be solved in ω . The other system variables then are obtained by direct insertion. For a pulse width modulated voltage this approach yields an effective voltage variation, which corresponds to the modulation ratio.

Irrespective of what is the prescribed quantity the accuracy and usability of the model depends on the quality of the measured and/or estimated efficiency data. In this paper experimental data in a rectangular area in the first quadrant of the ω - τ plane are used. In the regions between this area and the ω - and τ -axis the following approach is proposed. The electrical machine supplier normally presents an equivalent 1-phase phase resistance R_0 . The friction torque T_0 can be assumed to be a fraction ε of the delivered torque plus a torque that is proportional to $\omega^{2/3}$ [3]. Due to eddy currents and skin effects the equivalent phase resistance increases proportionally to $(1 + (\omega/\omega_c)^2)$. The iron losses is proportional to $B_0^2(k_1\omega^2 + k_2\omega)$. Also one can assume a load-independent switching loss P_0 . The load-dependent switching losses can be described by an effective ε . An expression of the total actuator efficiency now can be written

$$\eta = \frac{\tau\omega}{\tau\omega(1 + \varepsilon) + A\omega^{5/3} + R\left(\frac{\tau}{t}\right)^2 \left(1 + \left(\frac{\omega}{\omega_c}\right)^2\right) + B_0^2(k_1\omega^2 + k_2\omega) + P_0} \quad (3)$$

On the borders of rectangular area facing at the ω - and τ -axis (3) yields another effective phase resistance R_e . The idea is to linearly interpolate R_e between R_l and R_0 along the straight line parallel to the ω -axis in the region between the rectangular area and the τ -axis. In the region between the rectangular area and the ω -axis, R_l is used along the straight line parallel to the τ -axis, because R_0 is given for $\omega=0$. In the rectangular area between origin and the lower left corner of the table area two successive interpolations along perpendicular lines were performed. In Fig. 2 an example is shown of original experimental values [4] combined with the values estimated by the described technique. The non-realistically high efficiency values near the ω -axis are a result of the rather rough modelling of the

mechanical loss mechanisms and can be lowered by a more detailed mechanical description of the actuator.

Any of the system variables or any combination of them can be the prescribed quantity. If one of ω , τ or I are prescribed one gets a single differential equation, which immediately gives the other unknowns. With appropriate efficiency data this means that the model also can be used when the actuator functions as an electric generator. In the given example a prescribed constant current is used. From the electric supply the actuator then can be regarded as a variable resistance.

Fig. 3 shows a numerical example, where an actuator is turned on and then loaded by an increasing viscous load until it is slowed down to ω near zero.

The presented modeling approach is considered to be computationally very efficient and is possible to extend to manage losses and features of the power supply system, the involved electrical machine, and the mechanical load in entire MEA aircrafts.

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Fig. 2. Experimental and estimated actuator efficiencies.

Fig. 3. Example of a simulated variation of actuator efficiency.

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