Improved MRAS based HI extraction method for PMSM of Electro-Mechanical Actuator

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***Abstract*—Electro-Mechanical Actuator (EMA) utilized in the flight control actuation is becoming more and more important in aerospace applications, especially for more electric aircraft. EMA Health Indicator (HI) extraction is challenging as the sensor installation is limited, which is a critical part of EMA Prognostics and Health Management (PHM). Model Reference Adaptive System (MRAS) is an effective parameter estimation method to extract HIs of Permanent Magnet Synchronous Motor (PMSM) of EMA, which can achieve high precision estimation with a small amount of calculation. However, the MRAS based HI extraction method is not suitable for stator resistance estimation of PMSM with Field-Oriented Control (FOC) strategy in which the expected d-axis current is zero. Hence, to deal with this problem, an improved MRAS is proposed for the HI extraction of stator resistance of EMA PMSM. In the proposed HI extraction method, the expected d-axis current of PMSM is set to a constant nearly zero, and the inputs of d-axis current of MRAS is substituted by the sum of a constant and d-axis current. Besides, the structure of adjustable model of MRAS is improved to cope with this sum. Furthermore, the estimated stator resistance based on improved MRAS, which is a useful HI for EMA PMSM, can be obtained. To evaluate the effectiveness of HI extraction method based on improved MRAS for EMA PMSM, two experiments are carried out using simulation data. The experimental results demonstrate that the improved MRAS based method is more suitable for HI extraction of EMA PMSM.**

***Keywords*—Prognostics and Health Management, Electro-Mechanical Actuator, Health Indicator, Parameter Estimation, Model Reference Adaptive System**

I. INTRODUCTION

In recent years, fly-by-wire technologies have draw growing attentions in aerospace applications [1]. Fly-by-wire control actuation has many advantages, for example, lower overall weight and better maintainability, which enable it more applicable for new-generation aircraft. Furthermore, Electro-Mechanical Actuator (EMA), which is a kind of fly-by-wire control actuation, has been used in many aerospace applications, such as civilian airliners and robotic spacecrafts [2]. Some EMAs have already been used in aircraft trim tab actuation, spoiler and etc. Besides, much efforts has been paid to apply EMAs in more critical roles in Airbus 380, Boeing 787 and F-35 Joint Strike Fighter, such as flight control actuation, landing gear and weapons bay door [3]. Besides, EMAs applied in aerospace applications require high reliability and safety [4]. However, due to that EMAs have not been applied for a long enough time and sufficient amount in aerospace fields to accumulate reliable fault statistics, their safety and reliability need to be further improved.

EMA Prognostics and Health Management (PHM) being able to minimize failures can help to achieve this goal and makes EMA more suitable in aerospace applications [5]. There are mainly two kinds of approaches included in EMA PHM (i.e., data-driven approaches and model-based approaches). Model-based approaches generally realize the estimation of health-related parameters through accurate mathematical models. The differences between the estimated parameters and the initial parameters for a healthy system can be used to indicate EMA faults or degradation [6]. For instance, Byington et al. propose a method for EMA parameter estimation, such as efficiency and damping. After that, the difference between initial parameters and their estimation is used to indicate EMA degradation degree [7]. Besides, compared with data-driven approaches, model-based approaches have more clear correspondence between failure modes and model parameters.

Health Indicator (HI) extraction is an important part of EMA PHM which can provide the degradation characterization ability. Many researchers have focused on HI extraction. For example, Doebling et al. present a review on HI extraction method based on signal processing [8]. Pawar et al. focus on HI extraction for helicopter rotor failures utilizing vibration signatures [9]. Wang et al. extract 11 HIs through residual error signals as well as a fused HI for gear degradation [10]. Tsui et al. study bearing performance degradation assessment and propose a useful HI [11]. For the HI extraction of EMA, Balaban et al. present different HIs based on monitoring data which can be used in fault diagnosis, such as Load Profile Indicator, Drift Indicator, Force Indicator, Temperature Deviation and Signal Standard Deviation [2]. Byington et al. focus on the research field of EMA HI extraction and propose four physical HIs including Local Gear Stiffness, Frictional Damping Coefficient, Motor Temperature and Torque Constant [7]. From the literature review, it can be concluded that the research of high-performance HI extraction methods is a critical part for the development of EMA PHM.

EMA HIs are mostly defined as internal physical parameters. However, these parameters cannot generally be directly monitored because of the limited sensor installation in aerospace applications [12]. Besides, it is also unrealistic to add specialized sensors to extract EMA HIs as it may reduce

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the mean time between failures of EMA [13]. Model Reference Adaptive System (MRAS) is one of the online parameter estimation methods widely utilized in the parameter estimation of Permanent Magnet Synchronous Motor (PMSM), which is able to achieve high precision estimation with a small amount of calculation [14]. Thus, it can be utilized to extract HIs of EMA PMSM. However, the MRAS based HI extraction method cannot be utilized to estimate stator resistance of PMSM with Field-Oriented Control (FOC) strategy in which the expected d-axis current is zero. In this study, an improved MRAS for HI extraction of stator resistance of EMA PMSM is proposed to address this issue, where the expected d-axis current of PMSM is set to a constant nearly zero, and the d-axis current inputs of improved MRAS is substituted by the sum of d-axis current and a constant. Besides, the structure of adjustable model of MRAS is improved to cope with the sum. Moreover, the estimated stator resistance based on improved MRAS can be obtained, which is regarded as a useful HI.

This paper consists of five sections. Section II shows the relevant methodologies including the mathematical model of PMSM and the principle of MRAS based estimation method for PMSM. Section III describes the framework of improved MRAS based estimation method. Section IV presents the experimental data and details as well as the results of HI extraction for the stator resistance of EMA PMSM. Section V presents the conclusion of this study and the future work.

II. Relevant Methodologies

A. Brief introduction of PMSM Model

The modeling for PMSM is important for FOC control of PMSM. Under following two assumptions, a d-q model of the PMSM can be obtained. Firstly, the nonlinearities caused by the location of the stator winding and the saturation of the iron can be neglected. Secondly, the stator windings should be sinusoidal distributed, and they are displaced by 120 degrees. The d-q model is shown as follows [15],

$$u_d = Ri_d + L_d\frac{di_d}{dt} - \omega L_q i_q, \tag{1}$$

$$u_q = Ri_q + L_q\frac{di_q}{dt} + \omega L_d i_d + \omega\psi_f, \tag{2}$$

where u_q and u_d represent the q-axis and d-axis voltages, respectively. i_q and i_d represent the q-axis and d-axis currents, respectively. R is stator phase resistance. L_q and L_d indicate the stator inductances of q-axis and d-axis, respectively. Generally, for surface mounted PMSM, L_d equals to L_q. ψ_f denotes the permanent magnetic flux of PMSM. ω represents rotor speed of PMSM. When treating i_d and i_q as the state variables, (1) and (2) can be redefined in the form of two state equations shown as follows [16],

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + \omega i_q + \frac{U_d}{L}, \tag{3}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q - \omega i_d + \frac{U_q}{L} - \omega\frac{\psi_f}{L}, \tag{4}$$

where L represents equivalent d-axis and q-axis stator inductances.

B. Principle of MRAS based estimation method for PMSM

In this part, the basic principle of MRAS based estimation method for PMSM is presented. The MRAS based estimation method for PMSM can be used to simultaneously obtain the estimation of the rotor flux linkage, stator resistance and inductance, and requires only monitoring data of voltage, current and rotor speed. Generally, MRAS consists of adaptive rate and adjustable model. Through choosing d-axis and q-axis current as PMSM state variables, the state model of PMSM can be rewritten as (5). The adjustable model of MRAS can be described in (6).

$$\dot{X} = AX + BU + C, \tag{5}$$

where $A = \begin{bmatrix} -\tau & \omega \\ -\omega & -\tau \end{bmatrix}$, $B = \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix}$ and $C = \begin{bmatrix} 0 \\ -e_f \end{bmatrix}$, respectively. $X = \begin{bmatrix} i_d & i_q \end{bmatrix}^T$ and $U = \begin{bmatrix} v_d & v_q \end{bmatrix}^T$ represent the current state vector and command vector, respectively. Besides, $c = \frac{1}{L}$, $\tau = \frac{R}{L}$, $e_f = \omega I_f$ and $I_f = \frac{\psi_f}{L}$.

$$\dot{\hat{X}} = \hat{A}\hat{X} + \hat{B}U + \hat{C} + G\left(\hat{X} - X\right), \tag{6}$$

where $\hat{A} = \begin{bmatrix} -\hat{\tau} & \omega \\ -\omega & -\hat{\tau} \end{bmatrix}$, $\hat{B} = \begin{bmatrix} \hat{c} & 0 \\ 0 & \hat{c} \end{bmatrix}$, $C = \begin{bmatrix} 0 \\ -\omega\hat{I}_f \end{bmatrix}$ and $G = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}$, respectively. G denotes a correction gain matrix which is utilized to realize the goal of pre-specified performance, in which k_1 and k_2 represent two positive real number. By subtracting PMSM adjustable model, i.e., (6), from PMSM state model, i.e., (5), the error function model can be obtained shown as follows,

$$\dot{e} = (A+G)\,e + \left(-\Delta A\hat{X} - \Delta BU - \Delta C\right), \tag{7}$$

where e represents the state error. ΔA, ΔB and ΔC denote the difference of A and $\hat{A}$, B and $\hat{B}$, and C and $\hat{C}$, respectively.

Based on error function model and POPOV stability theory, the adaptive rate can be designed in a similar way as PI controller. The adaptive rate of MRAS is presented as follows,

$$\frac{\hat{R}}{\hat{L}} = \frac{R}{L} - K_1'\int_0^t e^T\hat{X}dt - K_2'\int_0^t e^T\hat{X}dt, \tag{8}$$

$$\frac{1}{\hat{L}} = \frac{1}{L} + K_1''\int_0^t e^T U dt + K_2''\int_0^t e^T U dt, \tag{9}$$

$$\frac{\hat{\psi}_f}{\hat{L}} = \frac{\psi_f}{L} - K_1'''\int_0^t e^T\begin{bmatrix} 0 \\ \omega \end{bmatrix}dt - K_2'''\int_0^t e^T\begin{bmatrix} 0 \\ \omega \end{bmatrix}dt, \tag{10}$$

where K_1', K_1'' and K_1''' represent proportional parameters of three PI controllers, and K_2', K_2'' and K_2''' are integral parameters of these three PI controllers. The global structure of MRAS based estimation method for PMSM is shown in Fig. 1.

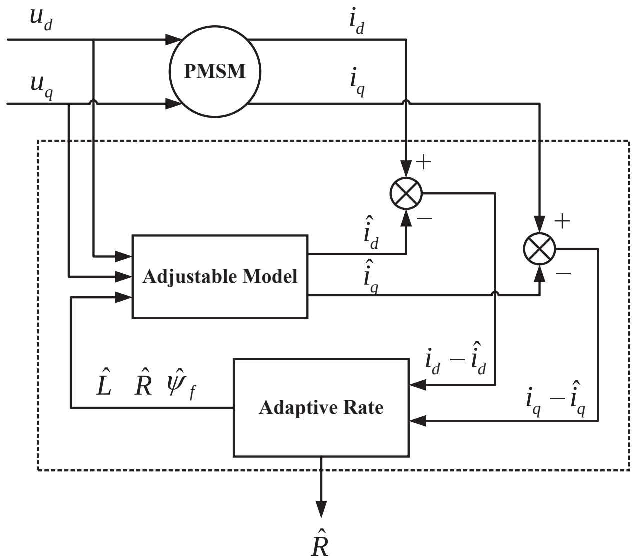

Fig. 1. MRAS based estimation method for PMSM.

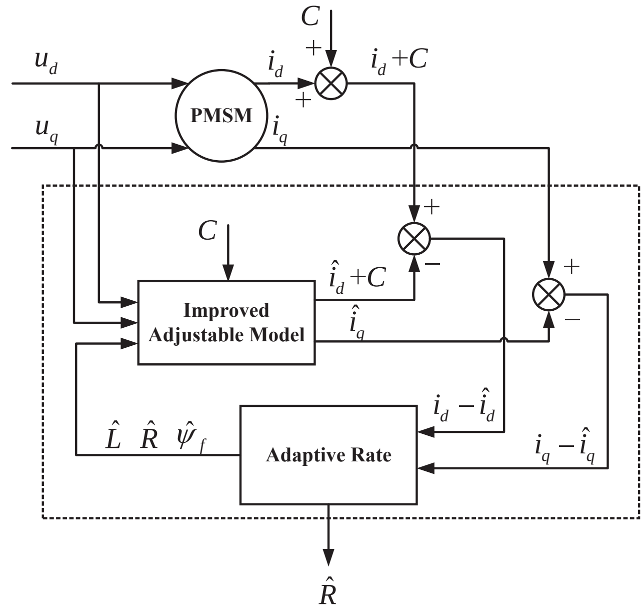

Fig. 2. Improved MRAS based estimation method for PMSM.

III. Framework of improved MRAS based method

In traditional MRAS method for stator resistance of PMSM, the d-axis current, i_d, cannot be zero. But i_d is expected to be zero in FOC control strategy, which is one of the general and classical control strategies for PMSM. An effective method to deal with this problem is to set i_d to a constant nearly to zero. However, this method will reduce convergence rate of the estimation process for stator resistance. Therefore, to deal with the challenge of MRAS based method for stator resistance estimation of PMSM, an improved MRAS method is proposed. In the improved MRAS method, i_d is set to a constant nearly to zero and the inputs i_d of improved MRAS is substituted by $i_d + C$, where C is a positive real number. Besides, the structure of MRAS is also improved to adapt to $i_d + C$ inputs. The PMSM model can be rewritten as follows,

$$\frac{di_d}{dt} = -\frac{R}{L}\left(i_d + C\right) + \omega i_q + \frac{U_d}{L} + \frac{R}{L}C, \tag{11}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q - \omega\left(i_d + C\right) + \frac{U_q}{L} - \omega\frac{\psi_f}{L} + \omega C. \tag{12}$$

So the adjustable model of improved MRAS can be designed as follows.

$$\frac{d\left(\hat{i}_d + C\right)}{dt} = -\frac{\hat{R}}{\hat{L}}\left(\hat{i}_d + C\right) + \omega\hat{i}_q + \frac{U_d}{\hat{L}} + \frac{\hat{R}}{\hat{L}}C. \tag{13}$$

$$\frac{d\hat{i}_q}{dt} = -\frac{\hat{R}}{\hat{L}}\hat{i}_q - \omega\left(\hat{i}_d + C\right) + \frac{U_q}{\hat{L}} - \omega\frac{\hat{\psi}_f}{\hat{L}} + \omega C, \tag{14}$$

where $\hat{i}_q$ and $\hat{i}_d$ represent the estimation of i_d and i_d, respectively.

The global structure of improved MRAS based estimation method for PMSM is shown in Fig. 2. Compared to MRAS, the input and output of the adaptive rate of improved MRAS remain unchanged. Therefore, the MRAS and improved MRAS has the same adaptive rate.

IV. Experimental Results and Analysis

A. The Simulation model of EMA

To validate the improved MRAS estimation method, a simulation model of PMSM based on simulink is used to instead of EMA simulation model, in which the PMSM is driven by a Pulse Width Modulation (PWM) inverter. Before applied to the stator windings, the output of PWM inverter goes through three controlled voltage source blocks. Besides, there are 2 control loops in this simulation model. The inner one is to regulate stator currents and the outer one is to control the speed. The simulation model of PMSM is shown in Fig. 3. The d-axis and q-axis stator voltage, d-axis and q-axis stator current and rotor speed can be obtained based on this PMSM simulation model shown in Fig. 4. The main parameters of

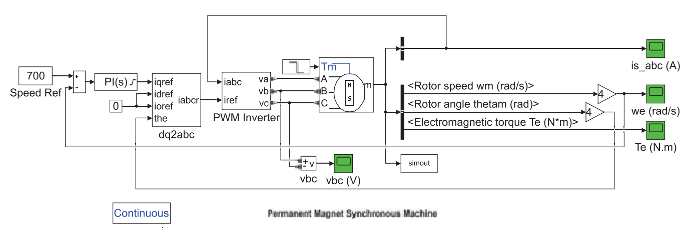

Fig. 3. Simulation model of PMSM.

the simulation model of EMA are shown in Table. I.

B. Stator resistance estimation based on MRAS

In order to evaluate the effectiveness of improved MRAS based HI extraction method for stator resistance of EMA PMSM, two experiments with simulation data are conducted. In experiment 1, MRAS based estimation method is utilized. The simulation model for MRAS based estimation method is

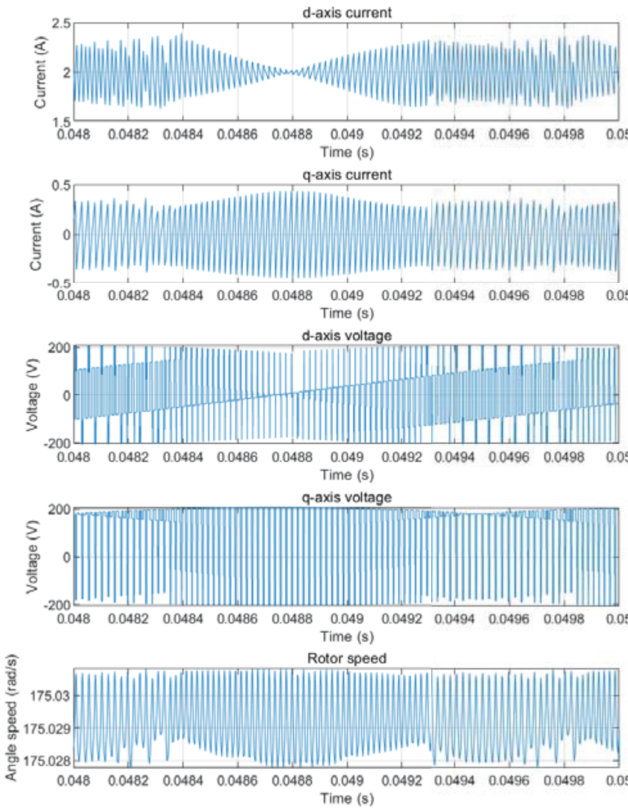

Fig. 4. Monitoring parameters of simulation model of PMSM.

TABLE I
THE MAIN PARAMETERS OF EMA SIMULATION MODEL.

Parameter Name	**Value**	**Unit**
Stator phase resistance	2.875	ohm
Armature inductance	0.00153	H
Flux linkage	0.175	Wb
Reference Speed	700	rad/s

presented in Fig. 5. The results of MRAS based estimation method for stator resistance of EMA PMSM are shown in Fig. 6.

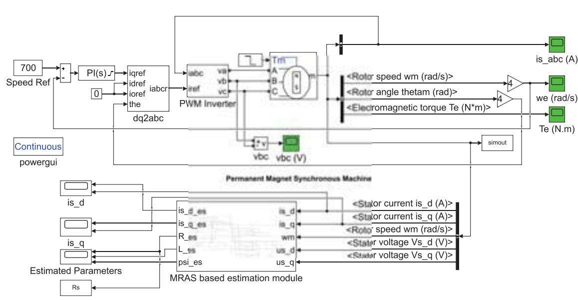

Fig. 5. Simulation model of MRAS based estimation.

In experiment 2, the improved MRAS based estimation method is utilized. The simulation model for improved MRAS

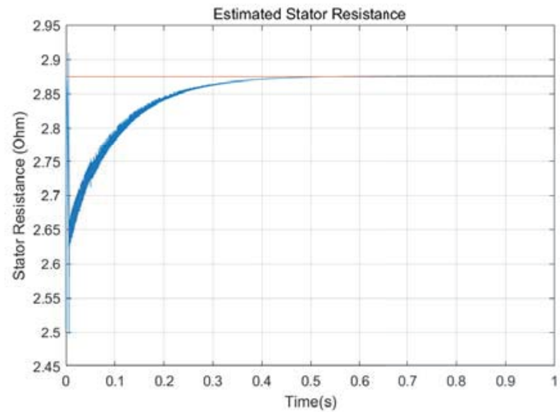

Fig. 6. Results of MRAS based estimation.

based estimation method is presented in Fig. 7. The results of improved MRAS based estimation method for stator resistance of EMA PMSM are shown in Fig. 8.

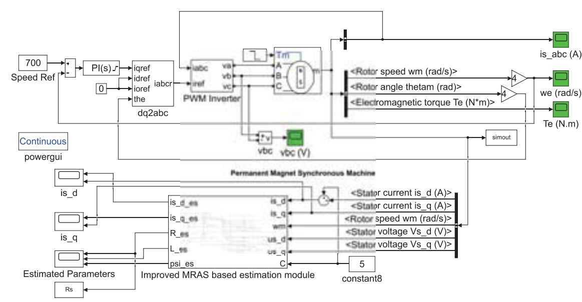

Fig. 7. Simulation model of improved MRAS based estimation.

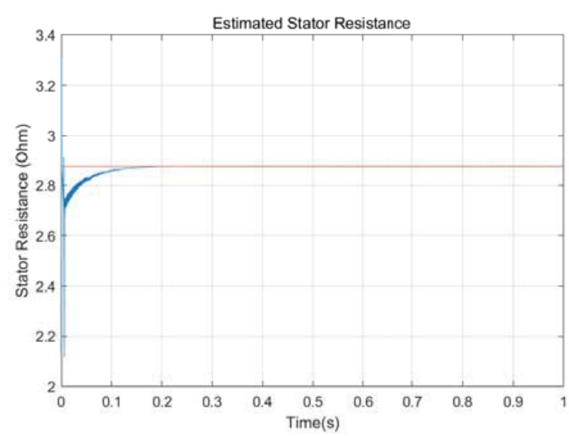

Fig. 8. Results of improved MRAS based estimation.

From Figs. 6 and 8, it can be seen that the convergence time of MRAS based estimation method is 0.51s, and the convergence time of improved MRAS based estimation method is 0.20s. Compared to MRAS based estimation method, the convergence rate of improved MRAS based estimation method is increased by 60.8%. Hence, the improved MRAS based estimation method is more suitable than MRAS based estimation method for HI extraction of EMA PMSM.

V. Conclusion

This study focuses on HI extraction for EMA PMSM. To characterize degradation degree of stator resistance for EMA PMSM, this study proposes an improved MRAS based HI extraction method. In the proposed method, the inputs and the model structure of MRAS has been improved to deal with the challenges of applied MRAS method into stator resistance for EMA PMSM. To validate the effectiveness, two experiments are carried out utilizing simulation data. Experimental results demonstrate that improved MRAS based HI extraction method has a good performance for EMA PMSM. Compared with MRAS based HI extraction method, the convergence rate is increased by 60.8%. Therefore, the proposed method provides a novel way for HI extraction of EMA PMSM, which can contribute to the EMA PHM improvement.

However, the practical application of the improved MRAS based HIs is not considered such as degradation modeling, remaining useful life prediction. In future work, we will focus on the research of the practical applications of extracted HIs.

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