INTELLIGENT ADAPTIVE CONTROL OF FLYWHEEL ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLES OPERATING IN NON-UNIFORM TERRAIN

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ABSTRACT

Flywheel Energy Storage Systems (FESS) is an interesting prospect for being used in Electric Vehicle (EV) so as to match the desired load curve of a transport vehicle. FESS involves high spin-speed rotors, which are supported by Active Magnetic Bearings (AMBs). Since the EVs are usually subject to base motion due to non-uniform road conditions, maneuvering of the vehicle, the base motions cause the time-dependent variations in the parameters to the FESS rigid rotor system. Designing an optimal controller for such systems may not be always possible because of the variety in the base motion amplitude and frequency. Therefore, this work proposes an adaptive Proportional Derivative (PD) controller for such rotors supported on Magnetic Bearings using a Fuzzy Inference System (FIS). The performance of the designed controller is compared with an optimal PD control law for different base motion conditions, and the test results reveal the superiority of the proposed intelligent controller over the conventional controllers.

Keywords—
ANFIS, Magnetic Bearings, Electric Vehicles, Flywheel Energy Storage System

I. INTRODUCTION

Flywheel energy storage systems (FESS) find wide range of industrial applications, namely, micro-satellites, electric vehicles and large power networks, etc [1]. FESS has three major components *viz.*, the rotor, the bearing and the power electronic interface, wherein Active Magnetic Bearings (AMBs) offer a contact-less support and levitation to the rotors, and, thereby, results in a low noise and energy efficient operation of the FESS [2]. For the application areas such as Electric Vehicles (EVs), the FESS and the AMB would inevitably be subject to the moving base conditions due to the motion of the EV and the irregular road disturbances. This large base motion, involving linear and angular motion of the EV, in-turn, would result in parametric excitation to the system, which may cause instability in the FESS-AMB system [3]. Moreover, this excitation gets compounded with the unbalance and gyroscopic forces acting on the FESS rotor bearing system. Designing an optimal controller for FESS-AMB in such a situation would not be straightforward owing to the varying system dynamics with different types of base motion which may often be of unpredictable nature and amplitude. This challenge sets the motivation for the present work.

The dynamics of rotors on conventional bearings subject to base motion has been dealt well with in literature such as [4], [5], [6], [7]. Fuzzy logic based controller has also been designed for an active magnetic system but for the case of rotor-magnetic bearing system mounted on a stationary applications ([8],[9], [10], [11]). However, the literature survey reveals that the case of rigid FESS rotor levitated by an AMB used for an EV where the base conditions are dynamic has not been carried out in any of the published literature thus far.

This paper therefore proposes an intelligent controller design using the Fuzzy Inference System (FIS) for the FESS mounted on an EV and subject to base excitation. To this end, the governing equations of motion for FESS system, involving rigid rotor with base motion, are first presented. Owing to the presence of moving base, the stiffness matrix and the damping matrix for the system are a function of time-varying base motion parameters. Next, the FIS based intelligent controller is designed, which adaptively tunes the gains of a PD control law. The performance of the proposed controller is evaluated on a simple FESS, comprising of a rigid rotor shaft system supported on an AMB. The simulated system is tested against various possible roll, pitch and yaw motion of the EVs. The test results reveal that the proposed intelligent controller is superior than the conventional PD controller in terms of vibratory response of the system and in terms of the amount of control current required by it.

The remaining of the paper is organized in six sections. Section II presents the governing equations of motion for rotor with base motion. In Section III, mathematical modeling of AMBs is presented. Fuzzy logic based adaptive control strategy is then discussed in section IV. Results and discussion is provided in section V. Key conclusions are finally drawn in Section VI.

II. GOVERNING EQUATIONS OF MOTION FOR BASE EXCITED ROTORS

An illustrative diagram of a simple rigid FESS rotor levitated by an an AMB and installed on an electric vehicle in motion is shown in Fig**. 1**. The governing kinematics and dynamics equations for rotors aboard a dynamic base has been derived in [4] and [6]. The equations of motion for the system is derived in following steps:

- Three different coordinate frames of reference are first defined in order to find the absolute velocity of the flywheel rotor disk.
- Absolute velocity of the flywheel rotor disk is found using kinematic relations.
- Finally, the governing equations of motion for the FESS mounted on a moving base is then derived using the Lagrange's principle.

The overall governing equations of motion are briefly presented as follows.

A non-inertial frame of reference is first defined as $\mathcal{C}(\hat{x}-\hat{y}-\hat{z})$ and is shown in Fig.1. A frame of reference attached to left AMB, which moves along with the rotor base is defined as $\mathcal{B}(\hat{p}-\hat{q}-\hat{r})$. A third frame of reference is attached to the rotor shaft and rotates with the rotor shaft is defined as $\mathcal{S}(\hat{u}-\hat{v}-\hat{w})$. The resulting equations of motion of the system are given as,

$$[\mathcal{M}]\{\ddot{\Lambda}\}+[\mathcal{D}(t)]\{\dot{\Lambda}\}+[\mathcal{K}(t)]\{\Lambda\}=\{f_{EV}(t)\}+\{f_{AMB}\} \tag{1}$$

where, $[\mathcal{M}]$ is the total mass matrix, comprising of rotor disk mass and moment of inertia, $[\mathcal{D}(t)]$ and $[\mathcal{K}(t)]$ are the time varying damping and stiffness matrix containing the time-varying base motion translational and rotational parameters, $\{f_{EV}(t)\}$ is the time varying force vector due to the EV base motion, $\{f_{AMB}(t)\}$ is the force vector acting on the system by virtue of the magnetic bearing and $\{\Lambda\}$ is the rotor shaft displacement vector. The complete form of these matrices are given below [6].

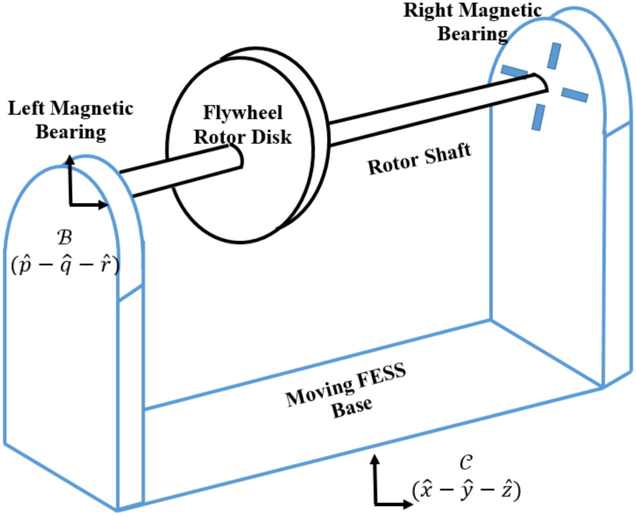

Fig. 1: Flywheel Energy Storage System supported by an AMB and installed on a moving EV.

The System matrices are given as follows,

The Inertia matrix, $[\mathcal{M}]=\begin{bmatrix} m_D & 0 & 0 & 0\\ 0 & m_D & 0 & 0\\ 0 & 0 & I_d & 0\\ 0 & 0 & 0 & I_d\end{bmatrix}$, The Gyroscopic matrix; $[\mathcal{G}]=\begin{bmatrix} 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -I_p\\ 0 & 0 & I_p & 0\end{bmatrix}$;

The Coriolis matrix $[\mathcal{L}] = \begin{bmatrix} 0 & -m_D & 0 & 0 \\ m_D & 0 & 0 & 0 \\ 0 & 0 & 0 & -I_d \\ 0 & 0 & I_d & 0 \end{bmatrix}$; The Stiffness matrix due to EV base motion, $\left[\mathcal{K}_{p11}\right]_D = \begin{bmatrix} m_D & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & I_p & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$; $\left[\mathcal{K}_{p22}\right]_D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & m_D & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I_p \end{bmatrix}$; $\left[\mathcal{K}_{p12}\right]_D = \begin{bmatrix} 0 & m_D & 0 & 0 \\ m_D & 0 & 0 & 0 \\ 0 & 0 & 0 & I_p - I_d \\ 0 & 0 & I_p - I_d & 0 \end{bmatrix}$. The Force vectors on FESS due to EV motion are given as,

$\left\{S_{2y}\right\}_D = [m_D x_D \; 0 \; 0 \; I_d]^T$; $\left\{S_{2p}\right\}_D = [0 \;\; m_D x_D - I_d \;\; 0]^T$; $\{S_{1Y}\}_D = \left[0 \; 0 \; 0 - I_p\right]^T$; $\left\{S_{1p}\right\}_D = \left[0 \; 0 - I_p \; 0\right]^T$; $\{S_1\}_D = [m_D \; 0 \; 0 \; 0]^T$; $\{S_2\}_D = [0 \; m_D \; 0 \; 0]^T$

The Global matrices and vectors are reproduced as,

$$[\mathcal{M}] = \textstyle\sum_D [M]_D + \sum_e [M]_S^e$$
$$[\mathcal{D}(t)] = \left(\Omega_{\hat{p}}^b + \dot{\phi}\right)\left(\textstyle\sum_D [\mathcal{G}]_D\right) + 2\,\Omega_{X_b}^b\left(\textstyle\sum_D [\mathcal{L}]\right)$$
$$[\mathcal{K}(t)] = -\left\{\left(\ddot{\phi} + \dot{\Omega}_{\hat{p}}^b\right)\{\textstyle\sum_D [H]_D\} - \dot{\Omega}_{\hat{p}}^b\{\textstyle\sum_D [\mathcal{L}]\}\right\} - \left\{\Omega_{\hat{p}}^{b^2}\{\textstyle\sum_D [\mathcal{M}]\} + \Omega_{\hat{r}}^{b^2}\left\{\textstyle\sum_D \left[K_{p11}\right]_D\right\} + \Omega_{\hat{q}}^{b^2}\left\{\textstyle\sum_D \left[K_{p22}\right]_D\right\} - \Omega_{\hat{q}}^b \Omega_{\hat{r}}^b \left\{\textstyle\sum_D \left[K_{p12}\right]_D\right\}\right\}$$
$$\{f_{EV}(t)\} = -\left(\dot{\Omega}_{\hat{r}}^b + \Omega_{\hat{p}}^b \Omega_{\hat{r}}^b\right)\left[\textstyle\sum_D \{S_{2Y}\}_D\right] + \left(\dot{\Omega}_{\hat{q}}^b - \Omega_{\hat{p}}^b \Omega_{\hat{r}}^b\right)\left[\textstyle\sum_D \{S_{2P}\}_D\right] - \left(\dot{\phi} + \Omega_{\hat{p}}^b\right)\left\{\Omega_{\hat{r}}^b\left[\textstyle\sum_D \{S_{1P}\}_D\right] - \Omega_{\hat{q}}^b\left[\textstyle\sum_D \{S_{1Y}\}_D\right]\right\} - \left(\dot{\mathrm{V}}_{\hat{p}}^b + \mathrm{V}_{\hat{p}}^b \Omega_{\hat{r}}^b - V_{\hat{r}}^b \Omega_{\hat{p}}^b\right)\left[\textstyle\sum_D \{S_1\}_D\right] - \left(\dot{\mathrm{V}}_{\hat{r}}^b - \mathrm{V}_{\hat{p}}^b \Omega_{\hat{q}}^b + \mathrm{V}_{\hat{q}}^b \Omega_{\hat{p}}^b\right)\left[\textstyle\sum_D \{S_2\}_D\right] - g(\cos\alpha_P \sin\gamma_R + \sin\alpha_P \sin\beta_Y \cos\gamma_R)\left[\textstyle\sum_D \{S_1\}_D\right] - g(\cos\alpha_P \cos\gamma_R - \sin\alpha_P \sin\beta_Y \sin\gamma_R)\left[\textstyle\sum_D \{S_2\}_D\right],$$

where, $\dot{\phi}$ is the rotor spin speed, $\Omega^b = \Omega_{\hat{p}}^b \hat{x} + \Omega_{\hat{q}}^b \hat{y} + \Omega_{\hat{r}}^b \hat{z}$ is the angular velocity of the EV base with respect to frame $\mathcal{C}$, $V^b = V_{\hat{p}}^b \hat{x} + V_{\hat{q}}^b \hat{y} + V_{\hat{r}}^b \hat{z}$ is the linear velocity vector of the EV with respect to frame $\mathcal{C}$.

III. MAGNETIC BEARINGS MODELLING

Magnetic bearings actively suspend rotors by sensing rotor displacement using proximity sensors. This sensed rotor displacement is then taken as feedback by the closed loop control system, and depending upon the dictating control law the controller decides the current to be given to the magnetic bearing electromagnets. This control current, in turn, decides the amount of electromagnetic force applied on the rotor shaft, so as to minimize the rotor shaft displacement. Basic components of a magnetic bearings include two pairs of electromagnets, proximity sensors, amplifier, converters. Figure 2 depicts this working principle of a magnetic bearing system, coupled with the controller block.

The linearized model of force applied by the magnetic bearings on the rotor shaft is given as,

$$f_{AMB}(t) = k_i i_c(t) - k_s \Lambda_{AMB} \tag{2}$$

where, k_i and k_s are constants associated with the magnetic bearing and are called as current stiffness and displacement stiffness, respectively, and are computed as-

- $k_i = 4k_{mag}\frac{i_0}{g_0^2}$;

- $k_s = -4k_{mag}\frac{i_0^2}{g_0^3}$,

where, i_0 is bias current value, g_0 is the nominal air gap existing between the rotor and the stator, $k_{mag} = \frac{\mu_0 A_p N^2}{4}$, A_p is the pole face are of the electromagnets, N is the number coil turns in each electromagnet.

The value of the control current $i_c(t)$ in (2) depends upon the underlying controller. Clearly, the performance of a magnetic bearing will be greatly influenced by the controller used for deciding the control current.

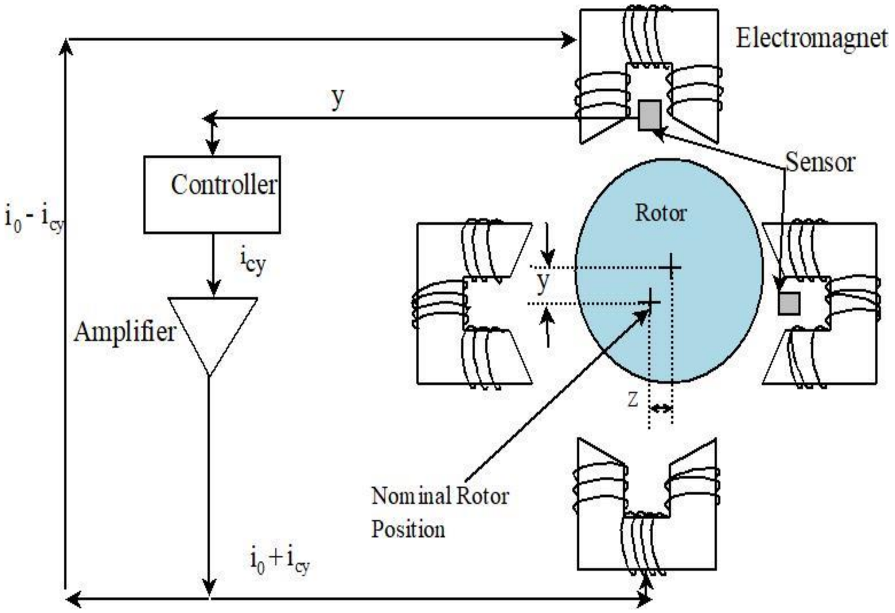

Fig. 2: Generic layout of an AMB-controller system.

IV. FUZZY LOGIC BASED ADAPTIVE CONTROL

Since the amount of disturbance which will be experienced by the EV base is fuzzy, and will heavily be dictated by the non-uniformity presented by the road conditions, and the driver's maneuvering abilities, an adaptive control is of the interest which can counter this time varying excitation due to EV motion. To this end, fuzzy logic has been exploited for designing an adaptive PD control of FESS rotor suspended on an AMB and mounted on an EV. The advantage of Fuzzy logic-based approach is that the procedure is intuitive and is useful in modeling the imprecision and uncertainty of the system. The design the adaptive PD controller involves the following main steps [12].

1. Fuzzy inference system (FIS) is first designed, which inherently is a relationship between a set of inputs and outputs, i.e., the fuzzy rules. In this work, two inputs are chosen, namely, the rotor displacement ($\Lambda_{flywheel}$) from its steady-state position and rotor disk velocity ($\dot{\Lambda}_{flywheel}$). The output of the FIS is chosen to be the PD controller gains (K_P, K_D).

2. The chosen input to the FIS is normalized using the following relation:

$$\begin{array}{ll} \text{Input 1} & \dfrac{\Lambda_{flywheel}}{g_0} \\ \text{Input 2} & \dfrac{\dot{\Lambda}_{flywheel}}{\omega g_0} \end{array} \qquad (3)$$

3. These inputs are then fuzzified by way of six triangular membership function viz., Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB) and is shown in Fig. 3.

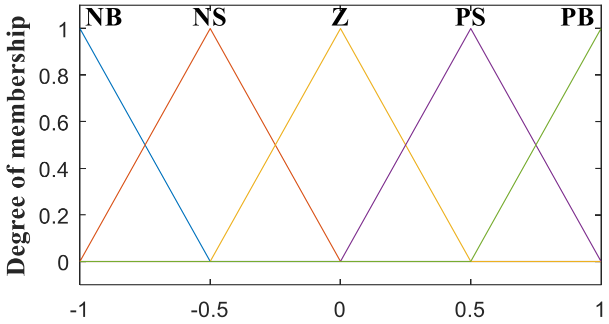

Fig. 3: Membership function for the input variables.

4. The outputs are also fuzzified with the help of three triangular membership functions, viz., Small (S), Medium (M) and Large (L).

5. Finally, based on process knowledge, the fuzzy rules which govern the input-output variables' relationship are designed. These fuzzy rules are tabulated in **Table I**.

Table I: Fuzzy rules relating the input and output variables.

IF Input 1 is	NB	AND Input 2 is	NB	THEN K_P is	L	AND K_D is	L
			NS		L		M
			Z		L		S
			PS		L		S
			PB		L		S
	NS		NB		M		L
			NS		M		M
			Z		M		S
			PS		S		S
			PB		S		S
	Z		NB		S		L
			NS		S		M
			Z		S		S
			PS		S		M
			PB		S		L
	PS		NB		M		S
			NS		M		S
			Z		M		S
			PS		M		M
			PB		M		L
	PB		NB		L		S
			NS		L		S
			Z		L		M
			PS		L		M
			PB		L		L

V. RESULTS AND DISCUSSION

A. *System Details*

In order to simulate the dynamics of assembly of the Flywheel Energy Storage System supported by an AMB and installed on a moving EV, a single rotor disk shaft is chosen [13]. The particulars of the mechanical assembly, which have been used in the simulation, are given in **Table *II***. Likewise, **Table *III*** lists out the particulars of the magnetic bearings system such as number of coil turns used, pole face are, bias current, etc., used for the simulation in the present work.

Table II: Rotor shaft details.

Table III: Magnetic bearing details.

Rotor Shaft Details	Shaft length	**1 m**
	Rotor disk diameter	0.2 m
	Disk polar moment of inertia	0.1 $kg\ m^2$
	Disk transverse moment of inertia	1.72 $kg\ m^2$
	Rotor shaft density	7810 $\frac{kg}{m^3}$
	Rotor shaft Young modulus	211 GPa

Magnetic Bearings	No. of coil turns	**5000**
	Pole face area	5 cm^2
	Bias current	5 A
	Rotor stator air gap	1 mm
	Current stiffness	227.47 N/A
	Displacement stiffness	4.55 $\times 10^5\ N/m$

B. *Time Response Comparison*

In order to compare the rotor response and control current for the adaptive FIS based controller and the non-adaptive PD control, following two different base motions are chosen as the test case. In both the cases the frequency and amplitude of EV motion is chosen to be 10 rad/s and 10°, respectively.

- **Case-1** considers the periodic pitching of the EV
- **Case-2** considers the periodic rolling motion of the EV.

Case-1 Results:

The plot of time response for the flywheel rotor **vertical** displacement for the periodic pitching **Case-1** is shown in Fig. 4. It can be observed from the results that due to the periodic pitching type of the base motion, the fixed PD controller results in an increasing vertical displacement of the rotor from its nominal position due to its fixed controller parameters, and the corresponding control current required by the AMB to bring back the rotor to its nominal position is also proportionally increasing, as shown in Fig. 5 (blue plot).

The efficacy of the adaptive FIS based controller, on the other hand, is clearly visible from the vertical displacement as well as the amount of control current required mitigates the vibrations of the FESS rotor from Figs. 4 and 5, respectively. The test results reveal that over a time, the proposed adaptive controller requires **nearly 1/4th** of the control current as compared to the fixed PD controller to mitigate the vibrations of the FESS rotor.

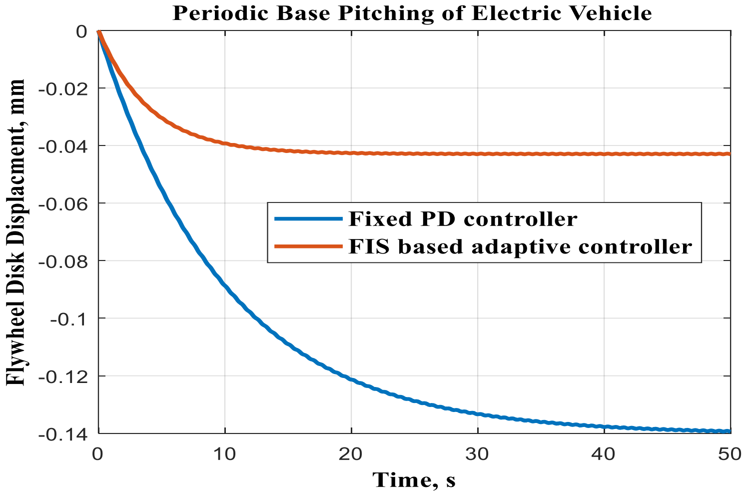

Fig. 4: FESS rotor disk vertical response due to Case-1 periodic pitching of the EV with fixed PD controller and adaptive controller.

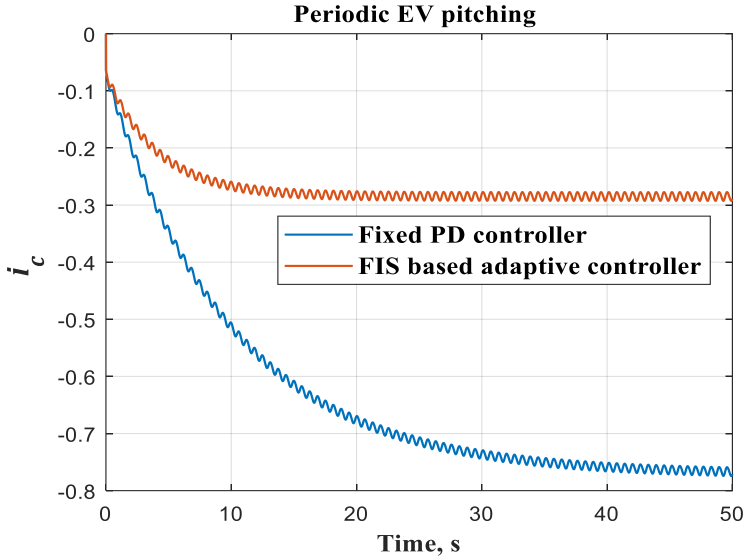

Fig. 5: Control current required by the AMB for controlling FESS rotor mounted on a pitching EV with fixed PD controller and adaptive controller.

Case-2 Results:

The **horizontal** response of the FESS rotor under the influence of periodic EV rolling motion is shown in Fig. 6 and the corresponding control current required by the horizontal coils of the AMB is shown in Fig. 7. It is observed that under these base conditions 1) the horizontal displacement of the rotor is very less (maximum of the order of $5 \times 10^{-3}\ mm$). However, the frequency of oscillations experienced by the FESS is very high, and 2) the adaptive FIS based controller performs better than the fixed PD controller in mitigating the vibrations in the system and at the same time requires comparable amount of control effort (if not less) in terms of control current.

The superior oscillation supressing capability of the proposed controller is clearly attributed to adaptive gains of the PD controller, resulted by the proposed adaptive FIS based controller. A plot of variation of the values of proportional gain K_P and derivative gain K_D for the PD control law, as resulted by the FIS for the periodic rolling case is shown in Fig. 8.

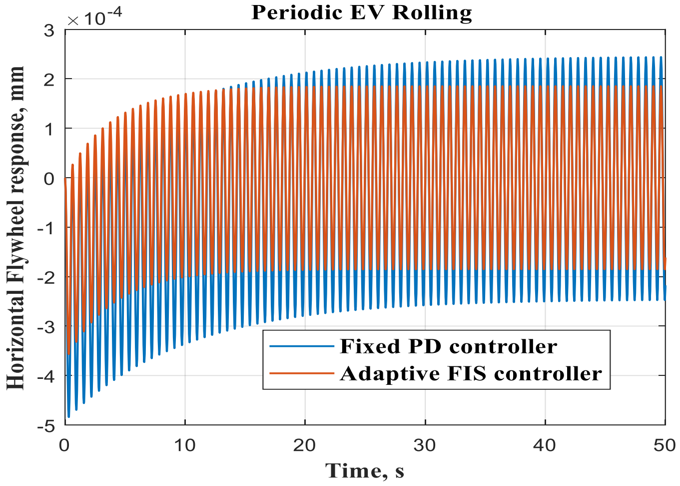

Fig. 6: Horizontal response of the FESS rotor to Case-2 periodic rolling of the EV with fixed PD controller and adaptive controller.

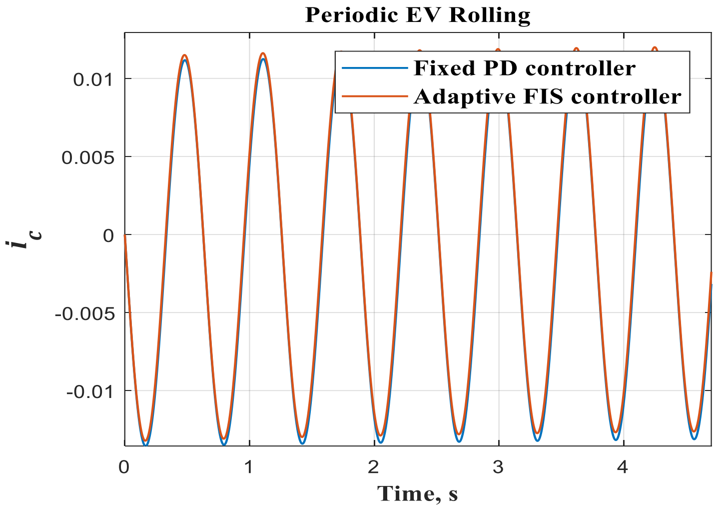

Fig. 7: Control current in horizontal AMB coils required for controlling FESS rotor under periodic EV rolling. The control current required by the adaptive controller is comparable to the fixed PD controller, if not less.

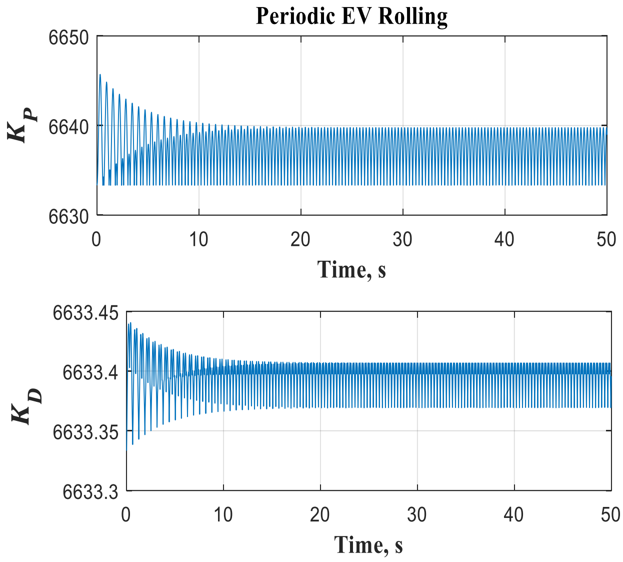

Fig. 8: Controller gains for the adaptive FIS controller for the case of periodic EV rolling.

VI. CONCLUSION

This work designs an adaptive controller using intelligent system framework of Fuzzy Inference System (FIS) for a FESS-Active Magnetic Bearing (AMB) onboard an Electric Vehicle (EV). Such a study is essential because time varying large base motion causes parametric excitation to the FESS rotor-AMB system which, in turn, can cause extreme vibration of the FESS rotor and raise stability concerns. Since there is a large variety of base motion conditions possible in such systems, it is difficult to design a fixed optimal control law for such cases. This work therefore presented a FIS based adaptive controller for FESS rotors levitated by AMBs and subject to base excitation due to the EV's inevitable motion. FESS rotor disk response comparison for the two cases, namely, the proposed adaptive controller and the fixed PD controller, is carried out. The control current required by the two controllers have also been compared. The numerical simulations have revealed the efficacy of the designed FIS based adaptive control law, which outperforms the fixed PD control law. Future work would include comparison of the FIS base adaptive control law with an optimal PD controller.

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