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Control of Flexible Rotor by Using Electromagnetic Actuators: Optimization of the Fuzzy Controller Gains

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Abstract

The aim is to set an optimization procedure for the determination of a fuzzy based controller gains. The objective function is defined as a combination of the maximum current, the displacements measured and the settling time. Two fuzzy based controllers were developed, the first has displacement and velocity as inputs (a fuzzy Proportional Derivative) and the second utilizes inputs expressed in polar coordinates. Its originality is that it manages two significant physical quantities, namely tangential and radial velocities, associated with steady state and transient behaviours respectively. The gains of the fuzzy PD controllers were determined by using optimization procedures that takes into account the mechanical behavior and the energy consumption. The gains (for the three controllers) were first determined by using numerical simulations, and then implemented for experimental testing. An additional tuning (in-situ) was necessary for the PD controller.

The performances of the two fuzzy based controllers were compared to a PD controller experimentally from mechanical and energy consumption points of view. The three controllers were efficient with a better behavior for the fuzzy based controllers for run up conditions. The optimization procedures are efficient and easy to implement in the case of PD fuzzy controllers, and must be enhanced to consider rules with different output, as in the case of polar fuzzy controller.

Keywords : Active Control, Fuzzy Controller, Electromagnetic Actuator, Rotordynamics, Vibrations, Polar transformation, PD Controller, Experiments

1. Introduction

Control devices (active or passive) are now much used in several fields of engineering where the quest to minimize energy requirements and satisfy the need to establish selection criteria for the "best" control approaches for a rotating machine have become a priority. AMBs are now widely used in different industrial applications and have been successfully implemented in the field of turbomachinery (Maslen, 2008, Swan, et al., 2008).

Several studies have been devoted to the elaboration of controllers that enable better design and performance in operating situations, with acceptable levels of stability and robustness (Nonami, et al., 1998, Schweitzer & Maslen, 2009, Defoy, et al., 2013). On the other hand, fuzzy controller approaches are well adapted for controlling flexible structures where the designer has some insight to characterize the general operation (Hung, 1995, Couzon & Der Hagopian, 2007, Dimitri, et al., 2015). Moreover, the advantages of fuzzy control are that it can be used in complex systems such as nonlinear, time-variant and systems including uncertainties. In addition, fuzzy controllers are less sensitive to variations of system parameters and they allow the utilization of membership functions adapted to the dynamic behavior of the system considered.

The main principles of the fuzzy approach are first the "*fuzzification*" of the inputs into linguistic quantities (Zadeh, 1965). Each input state is associated with a mathematic membership function. Second, the inference engine implements a set of linguistic rules based on the behaviour of the system. These rules are conditional and must describe all the possible events that can occur. This evaluation requires solid knowledge of the system that represents the major step for the elaboration of efficient fuzzy controller. Several studies were dedicated for the optimal choice and optimization of fuzzy controller parameters. Chen et al. (2009) proposed a design for a fuzzy gain tuning mechanism dealing with the problem of unbalanced vibration problem in an active magnetic bearing system. They replaced the conventional PID controller with a self-tuning fuzzy PID-type controller. Qiao and Mizumoto (1996) described a structure where the fuzzy PD- and PI-type controllers are simply connected together in parallel. They utilized the product sum inference method, center of gravity defuzzification method, and triangular uniformly distributed membership functions.

The aim of this work is to optimize the parameters of the fuzzy controllers. The system studied is an academic test rig with a hybrid bearing, where the control forces are applied by using an Electromagnetic Actuator (EMA). The structure proposed by Qiao and Mizumoto was adapted for the control of system studied. The gains are optimized considering the mechanical behavior (settling time, maximum displacement and stability) and the energy consumption that become, in our opinion, an important criteria for the selection of efficient controllers (Mahfoud, et al., 2011). Three controllers are studied: a classical Proportional Derivative (PD) controller, a Fuzzy based PD controller and a polar fuzzy controller. The originality of this methodology is that it manages two significant physical quantities, namely tangential and radial velocities, which are associated to steady state and transient behaviours respectively.

First studied system will be presented, then the control strategies and the optimization procedures will be described, and we will conclude by the experimental results obtained and the discussion.

2. Experimental test rig

The study was carried out on an academic test rig (Fig. 1) composed of a horizontal flexible shaft of 0.04 m diameter containing two rigid discs (D1 and D2). The rotor is driven by an electrical motor that can accelerate the shaft until the rotation of 10,000 rpm. The shaft is supported by bearings located at its ends, as follows: a roller bearing (B2) near the drive end and two ball bearings at the other end (B1). The roller bearing (B2) is located in a squirrel cage attached to the framework of the test bench by three identical flexible steel beams. The Electro-Magnetic Actuator (EMA) located at the external cage constitutes a smart active bearing (hybrid bearing) and enables the control and the excitation of the test rig.

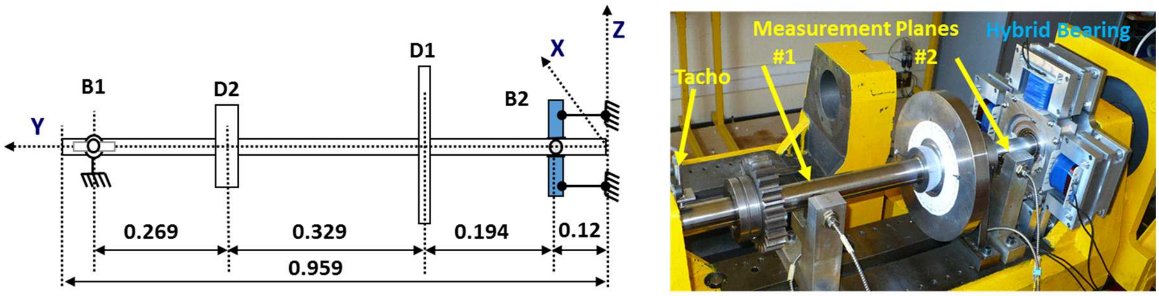


Fig.1 Experimental test rig details

Since an EMA can only produce attractive forces, four "identical" EMA supplied by constant currents are utilized. Each EMA is composed of a ferromagnetic circuit and an electrical circuit. The ferromagnetic circuit has two parts: an (E) shape, which receives the induction coil, and an (I) shape, which is fixed to the squirrel cage. Both parts are made of sets of insulated ferromagnetic sheets. The quality of the ferromagnetic circuit alloy is considered high enough and the nominal air gap between the stator and the beam is small enough so that the magnetic loss is considered negligible.

The displacements are measured by using four proximity sensors (Vibrometer TQ 103) arranged perpendicularly in two measurement planes located along the y axis, namely, measurement plane #1 and measurement plane #2 (fig. 1). The sensors are labeled C1 and C4 for the horizontal direction and C2 and C3 for the vertical direction.

The real time data acquisition and signal processing is performed by using cards dSpace®, as described in the following: a calculation card (DS1005) equipped with a digital signal processor (DSP TMS320C40), a 12 bit acquisition card (DS2002) with analog to digital time conversion rate of 3.3μs per channel, a 12 bit restitution card (DS2101) with digital to analog time conversion rate of 3.3μs per channel.

The behavior up to 10000rpm was considered in this study. The two first bending modes are included in this frequency range. The sampling frequency was set to 2e-4 seconds (5000Hz) which was high enough to avoid using anti-aliasing filters for the frequency range studied and allows for real time response monitoring.

Two types of excitation were considered:

1- unbalance response due to the initial unbalance (that was not identified) during run-up from 0 to 3500 rpm with constant acceleration in 40 seconds;

2- impulse response when the rotor was at a constant speed of 2200rpm which represents a stable operating zone before the first critical speed. The impulse is introduced by a step excitation of 3A amplitude (that corresponds to 100 N) applied simultaneously on both X and Z directions with 3.4ms duration.

3. Control strategies

Three control strategies were assessed. The first is a Proportional and Derivative (PD) controller that will be considered as the reference. A PD fuzzy based controller and a polar fuzzy controller. The general structure of the three controllers is presented in Fig. 2.

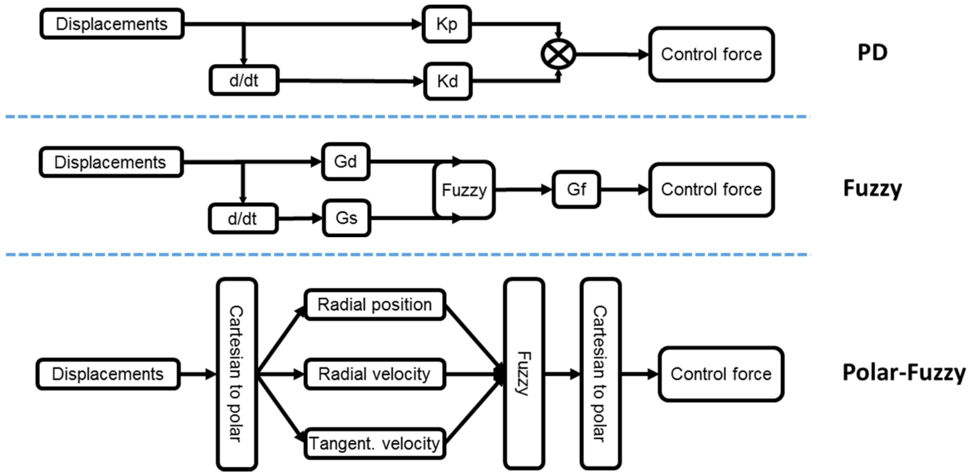


Fig. 2 Structure of the three controllers assessed

3.1. PD controller

The controller is simple and is designed to provide damping and stiffness. The gains were determined by optimizing the settling time (t_{98}) and the percentage of maximum overshoot using pole placement procedures. In this case, two SISO controllers were necessary in order to control the displacement following the X and Z direction. The optimal controller in the Laplace domain is:

$$H_{PD} = 1.16 \times 10^{6} \left(1 + 0.014\, S\right) \tag{1}$$

It is worth mentioning that the gains the pole were determined by using numerical simulations, but additional tuning was necessary when the controller was implemented for the experiments.

3.2. PD fuzzy controller

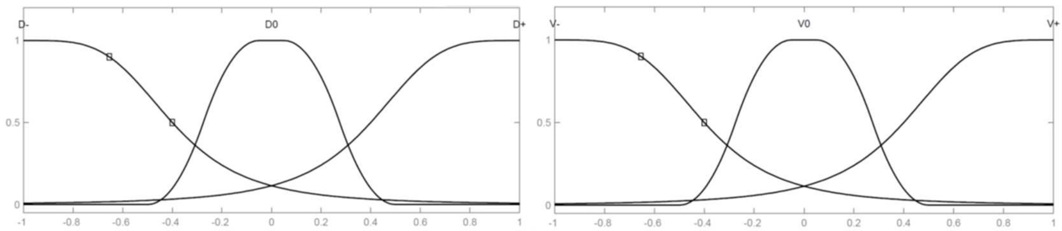
It is a fuzzy adaptation of the PD controller. The displacement and velocity were used as inputs for the fuzzy controller. The displacement was measured and the velocity calculated by numerical derivation (as in the previous case). Six generalized bell shape membership functions were utilized (Matlab®). These membership functions were associated with four fuzzy sets: positive/negative displacements and positive/negative velocities. In order to take into account the presence of measurement noise a specific membership function is added aa a dead-zone (Fig. 3).

The design of a membership function takes into account the measurement of noise. Membership functions have been adapted after several tests with white noise in order to prevent its influence in case of weak vibration levels. In order to be efficient small amplitudes of displacement and velocity should belong wholly to one of the two fuzzy sets (positive or negative). Finally, as nominal behavior is considered and, the displacements and velocities are relatively small compared to the measurement noise, only two membership functions were utilized for each input of the fuzzy controller.

The rules were chosen in order to optimize the energy dissipation and minimize the kinetic energy of the rotor (the force sign is always opposite that of the velocity). The rules selected were:

1- if displacement is positive and velocity is positive, then action;

2- if displacement is negative and velocity is negative, then action;
3- if displacement is positive and velocity is negative, no action;
4- if displacement is negative and velocity is positive, no action.
5- if any is the dead-zone, then no action.



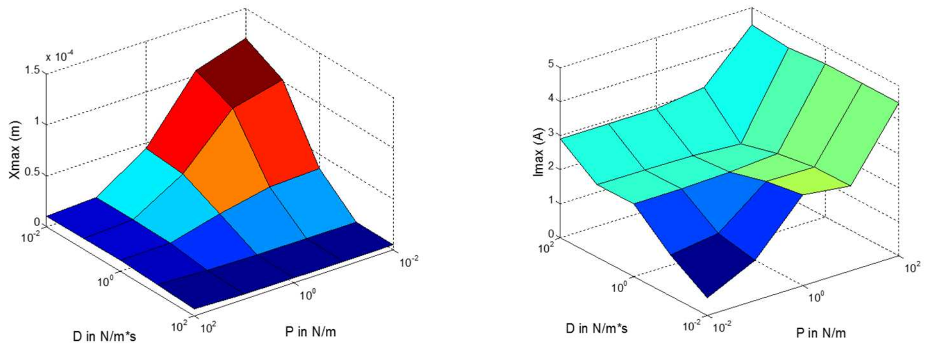
Displacements Velocities

Fig. 3 PD Fuzzy controller membership functions

Action is defined by the following relationship:

$$F_{Action} = G_f \left(G_d \times displacement + G_v \times velocity \right) \quad (2)$$

In order to determine the gains, a preliminary numerical study was done. During a run up from 2000 to 5000rpm in 45 seconds, the maximum values of the displacements and the consumed currents were calculated as a function of the variation of the total gain of the displacement (G_f x G_d), that is considered as a proportional gain (P), and the velocity (G_f x G_v), that is considered as a derivative gain (D). This study shows that there is values of these gains that will lead to an optimized behavior in performance and energy consumption.



Displacement variations Current variations

Fig. 4 Variation of maximum displacements and maximum current as a function with respect to controller gains variation

For this aim, a pseudo-random technique known as Particle Swarm Optimization (PSO) was used to adjust the controller gains. This technique was developed by the social psychologist James Kennedy and the electrical engineer Russel Eberhart (Kennedy and Eberhart, 1995). The design parameters are the controller gains, and the design space is defined by the values obtained previously. The objective function is defined as a function of the maximum current I_{max}, the displacements measured in both directions at the EMA position and the settling time t_{95}:

$$OF = I_{\max} + \sqrt{Z^2 + X^2} + t_{95} \quad (3)$$

The optimization procedures lad to G_f = 5, G_d= 3e-4 and G_v= 60. It worth mentioning that the gains obtained here are the same used during the experimental validation.

3.3 Polar fuzzy controller

Generally, the response of the system in acceleration or displacement is measured by using sensors placed along the structure. Regarding lateral behavior, two sensors oriented in two perpendicular axes are sufficient to describe the dynamic behavior. Then, the measured signals are processed and analyzed in time, frequency or time-frequency domains.

We assume that this approach is quite suitable for non-rotating structures, but when dealing with rotating machinery there is a lack of information on rotational speed. This lack can be compensated by describing the response measured in the polar coordinates. Observation of the measurements in the polar domain can lead to easier interpretation of the dynamic behavior, where the steady state and the transient behaviors can be distinguished directly, particularly in the case of real-time controlled systems.

The transformation from Cartesian to polar representation is obtained classically as indicated in (4). Where X and Z are the measured displacements along directions x and z in the Cartesian representation, while r and θ are the corresponding polar quantities.

$$r = \sqrt{X^2 + Z^2}$$
$$\tan\theta = \frac{Z}{X} \qquad (4)$$

Then the radial and the tangential velocities, V_r and V_t respectively, are calculated as follows:

$$V_r = \dot{r}$$
$$V_t = r\,\dot{\theta} \qquad (5)$$

where $\dot{r}$ is obtained by numerical differentiation of the radial position.

In a steady state case and in the presence of synchronous excitation as unbalance, the orbit is circular (symmetric rotor), and the radial displacement is constant, thus the radial velocity is nil while the tangential velocity is constant. It is noteworthy that in the case of system dissymmetry, the orbit of displacement is elliptical and the radial speed, position and tangential speed have harmonic variations that correspond to the second harmonic of the rotating speed.

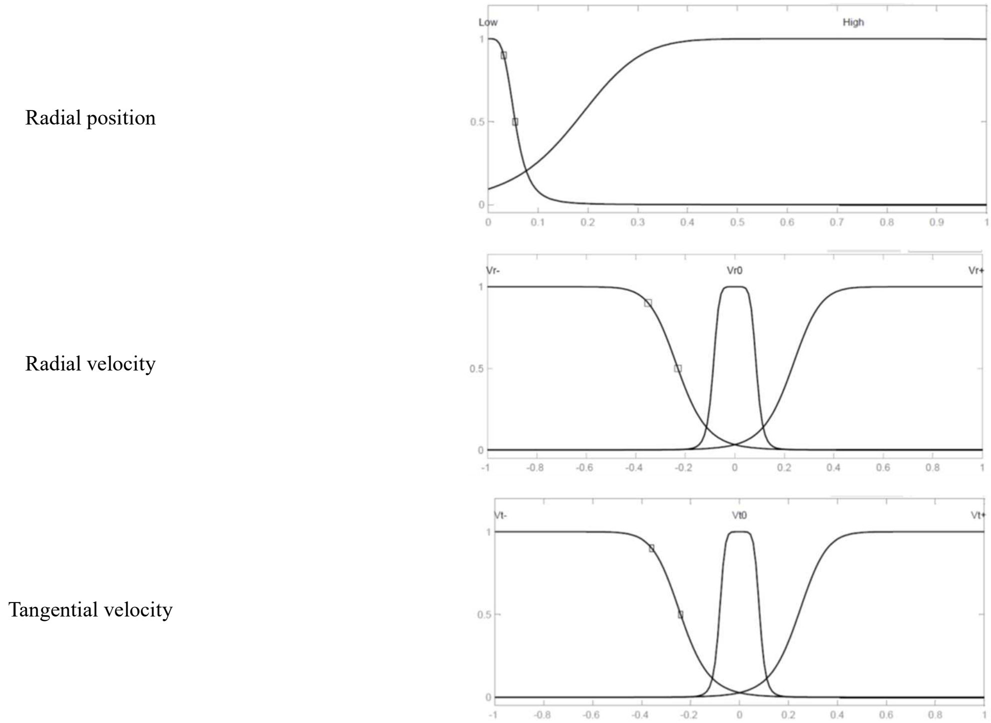


Fig. 5 Polar fuzzy controller membership functions

Actuation in the polar domain also has several advantages as it introduces targeted action on stiffness and damping. In this work, the controller was developed in the polar coordinate system, while measurements and actuation were still performed in the Cartesian coordinate system. This was due to the fact that the technology used was designed to operate in one direction.

The physical quantities introduced by polar transformation enabled the controller to distinguish the disturbance produced by the unbalance from the transient disturbance exciting the rotor radially. Indeed, when the rotor was subjected only to unbalance excitations, the rotor orbit was circular and the radius of the whirl orbit was constant or changed slowly during run up. The radial velocity was almost nil and the variations were only due to the measurement noise. Velocities (radial and tangential) are also sensitive to noise measurements, that is why a specific membership function (dead-zone) is added in order to limit their effects. Numerical simulations and experiments have shown that all polar quantities will be affected in the presence of impact excitation, while when crossing critical speeds and the changes of processing direction, the tangential damping is needed. Five membership functions were utilized (Fig. 5). The rules selected were:

1- if radial position is low and radial and tangential velocities are of the same order as noise, then action1;
2- if radial position is high and radial and tangential velocities are positive, then action2;
3- if radial position is high and radial and tangential velocities are negative, then action2;
4- if any velocity is the dead-zone, then no action.

Actions1 is designed to introduce damping essentially, and action2 is designed to introduce damping and stiffness:

$$Action1 = \begin{cases} F_t = 3 \cdot V_t \\ F_r = 7 \cdot V_r \end{cases}$$
$$Action2 = \begin{cases} F_t = 5 \cdot V_t \\ F_r = 0.5 \cdot r + 8 \cdot V_r \end{cases} \qquad (6)$$

The gains optimization procedures were not applied here. The procedures have to be adapted in order to take into account the presence of three physical quantities (r, V_r and V_t) and two different actions.

4. Experimental results

The study was first performed numerically and then validated experimentally. In this paper, only experimental results are presented. The performances of the two fuzzy based controllers were compared with the PD controller. Several tests were performed, here only two configurations will be presented:

1) unbalance response during run-up from 0 to 3500 rpm with constant acceleration in 40 seconds. Displacement at plane #2, along Z direction (sensor C3) in time domain is observed. In order to obtain a relative importance for the three controllers, the maximum displacements and the rms values of the displacement and the current consumed are compared taking as reference the maximum value (Fig.6). Same trends were observed in X direction.

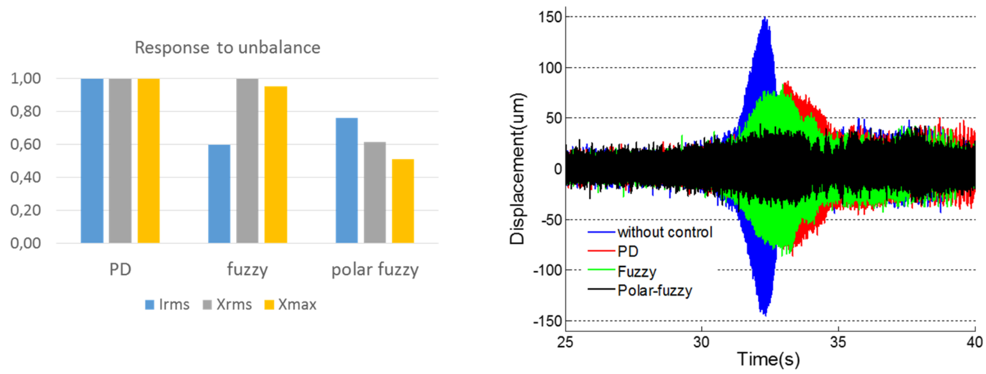


Fig. 6 Unbalance response due to run up from 0 to 3500rpm in 40 seconds, Z direction. Comparison of rms values of current and displacement and maximum displacement for the three controllers

The controllers are efficient. The residual level of vibration when crossing the critical speed is less than 180µm peak-to-peak. Slight advantage for the polar fuzzy controller in both mechanical performances (displacement) and energy consumption (current). On the other hand, an additional tuning was necessary for the PD controller when it was implemented for the experimental testing, where fuzzy based controllers were implemented directly, no additional tuning. The experiments were performed using gains determined by numerical simulations.

2) impulse response when the rotor was at a constant speed of 2200rpm. The impulse is introduced by a step excitation

of 3A amplitude (that corresponds to 100 N) applied simultaneously on both X and Z directions with 3.4ms duration. Displacement along Z direction in time domain (sensor C3) is observed and then, the maximum displacements, the rms value of current consumed and settling time are compared for the three controllers (Fig.7). Same trends were observed in X direction.

Here also, it could be seen that the controllers are efficient. Nevertheless, PD controller exhibits the best mechanical behavior and, from consumption point of view, the fuzzy controller presents the best performances.

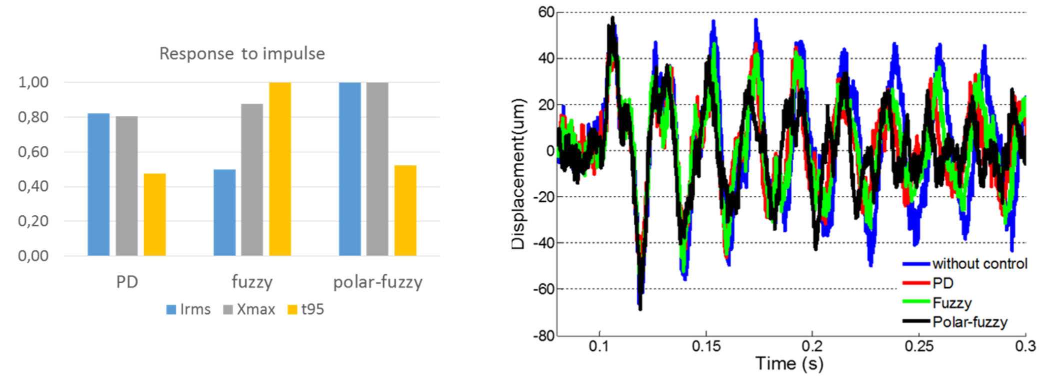


Fig. 7 Impulse response of 100N amplitude along X and Z directions at constant speed of 2200rpm, Z direction

5. Conclusions

The performances, from mechanical and energy points of view, of two fuzzy based controllers were compared to a PD controllers experimentally. The gains of the PD fuzzy controllers were determined by using optimization procedures that takes into account the mechanical behavior and the energy consumption. The gains (for the three controllers) were first determined by using numerical simulations, and then implemented for experimental testing. An additional tuning (in-situ) was necessary for the PD controller. The performances were compared for two configurations: run up crossing the first critical speed and an impulse while the rotor was in steady state at 2200rpm. The three controllers were efficient with a better behavior for the fuzzy based controllers for run up conditions.

The optimization procedures are efficient and easy to implement in the case of PD fuzzy controllers, and must be enhanced to consider rules with different output, as in the case of polar fuzzy controller.

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