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Research Article

An Enhanced Fractional Order Model of Ionic Polymer-Metal Composites Actuator

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Ionic polymer-metal composites (IPMCs) are electroactive polymers which transform the mechanical forces into electric signals and vice versa. The paper proposes an enhanced fractional order transfer function (FOTF) model for IPMC membrane working as actuator. In particular the IPMC model has been characterized through experimentation, and a more detailed structure of its FOTF has been determined via optimization routines. The minimization error was attained comparing the simple genetic algorithms with the simplex method and considering the error between the experimental and model derived frequency responses as cost functions.

1. Introduction

In the last decade a new breed of polymers, known as electroactive polymers or more commonly EAPs, has emerged thanks to their electroactive capabilities [1]. Ionic polymer-metal composites [2] belong to this material class. They bend if they are solicited by an external electric field and they act as motion sensor if an external deformation is applied. They are characterized by several interesting properties such as high compliance, lightness, and softness. IPMCs exploit ionic polymers for electrochemical and mechanical transduction and noble metals as electrodes, and they represent a valid alternative to the classic actuators and/or sensors. They can be cut in any shape and size, they are characterized by large deformations applying very low level of voltage, and they can work both in a humid or in a wet environment. These properties make them particularly attractive for possible applications in very different fields such as robotics, aerospace, and biomedicine [3, 4].

An intense research has been currently carried out to improve the IPMC performances in terms of power consumption, developed force, and deformation [5].

Moreover the research efforts have been spent in finding improved models able to predict the IPMCs behavior both as actuators and sensors [6].

In the literature several models describing the IPMC as actuator can be found. In detail, they can be divided into three categories: white box, black box, and grey box.

The first category, called white box, or physical models, is based on the underlying physical mechanisms of the IPMC to develop a system of equations that fully describes the device response [7]. Numerical implementation via methods as finite element analysis can be found in the literature [8]. Some difficulties are presented with physical modeling of IPMC transducers, such as a complete knowledge of the chemical and/or physical mechanisms involved in the electromechanical transduction and the direct measurement of some material parameters; moreover the numerical implementations are computationally onerous due to the distributed nature of the problem solution.

The second approach for modeling IPMC actuators is called black box and uses a linear [9] or differential [10] equation to simulate the actuating behavior. Such models, called also empirical and phenomenological, are based on the identification of coefficients through a series of curve fits based on the experimental data. The internal physics is, in this case, just a minor consideration.

An alternative to the complicated physical models and the simplistic and not scalable empirical models is the grey-box models. They comprise the fundamental physical laws into time-domain equations or transfer functions and empirically identified parameters to describe IPMC electromechanical behavior [11].

The grey-box model identification is often a multiobjective optimization problem in a multidimensional space since multiple cost functions can be used for parameters optimal estimation.

In a previous work, see [12], the authors have already proposed a fractional grey-box model of an IPMC actuator. In the present paper two novelties, with respect to [12], are introduced. The first one is related to the data acquisition. In fact instead of using, as input, a chirp signal it was applied a step-by-step frequency sweep. The second one is related to the structure of the interpolating FOTF; in this paper a further term has been added to the FOTF, obtaining a more accurate measurement fitting.

A very popular method in the field of parameter identification is the Nelder-Mead unconstrained simplex algorithm [13]. The method works on the exploration of the design space and does not require any derivative information, being therefore suitable for problems with nonsmooth functions. It is widely used in optimization software tools (i.e., MATLAB) to solve parameter estimation and similar statistical problems, when the function values come from experimentation and are thus uncertain or subject to noise [14]. On the other hand, the simplex method is prone to local minima issues, and the lack of convergence theory is often reflected in practice as a numerical breakdown of the algorithm, even for smooth and well-behaved functions.

Genetic algorithms (GAs), that explore a poorly understood solution space in parallel by intelligent trials, represent a class of optimization procedures able to face nonconvex optimization problem and to provide optimal solution avoiding remaining trapped in local minima [15, 16].

In the following, the two methods have been applied and compared in order to optimize the parameters of the interpolating FOTF.

The paper is structured as follows. Some introductive notes on fractional order systems are given in Section 2. A view on IPMC physics and working principles is presented in Section 3 in order to give an introduction on such a composite material; moreover the description of the experimental setup is given as the basis for understanding the experimental data used for model identification. In Section 4 the optimized FOTFs of the IPMC membrane are given, and finally some conclusions are reported.

2. Fractional Order System

The subject of fractional order calculus or noninteger order systems, that is, the calculus of integrals and derivatives of any arbitrary real or complex order, has gained considerable popularity and importance during the last three decades with applications in numerous seemingly diverse and widespread fields of science and engineering [17–19].

Fractional derivatives provide an excellent tool for the description of memory and hereditary properties of various materials and processes. This is the main advantage of fractional derivatives in comparison with classical integer-order models, in which such effects are in fact neglected. The advantages of fractional derivatives become apparent in modeling mechanical and electrical properties of real materials.

The most frequently used definition for the general fractional differintegral is the Caputo one, see [19]:

$$ {}_aD_t^r f(t) = \frac{1}{\Gamma(r-n)} \int_a^t \frac{f^{(n)}(\tau)}{(t-\tau)^{r-n+1}} d\tau, \tag{1}$$

for $(n-1 < r < n)$. The initial conditions for the fractional order differential equations with the Caputo derivatives are in the same form as for the integer-order differential equations.

In the above definition, $\Gamma(m)$ is the factorial function, defined for positive real m, by the following expression:

$$\Gamma(m) = \int_0^\infty e^{-u} u^{m-1} du. \tag{2}$$

Also for fractional order systems it is possible to apply the Laplace transformation. It assumes the form

$$L\left\{\frac{d^q f(t)}{dt^q}\right\} = s^q L\{f(t)\} - \sum_{k=0}^{n-1} s^k \left[\frac{d^{q-1-k} f(t)}{dt^{q-k-1}}\right]_{t=0} \tag{3}$$

and allows to easily manage fractional differential equation as noninteger order transfer function.

The fractional order transfer function of *incommensurate* real orders assumes the following form [18]:

$$G(s) = \frac{b_m s^{\beta_m} + \cdots + b_1 s^{\beta_1} + b_0 s^{\beta_0}}{a_n s^{\alpha_n} + \cdots + a_1 s^{\alpha_1} + a_0 s^{\alpha_0}}, \tag{4}$$

where a_k $(k = 0, \ldots, n)$, b_k $(k = 0, \ldots, m)$ are constant and α_k $(k = 0, \ldots, n)$, β_k $(k = 0, \ldots, m)$ are arbitrary real or rational numbers, and without loss of generality they can be arranged as $\alpha_n > \alpha_{n-1} > \cdots > \alpha_0$ and $\beta_m > \beta_{m-1} > \cdots > \beta_0$.

Since in this case the values of fractional exponents need to be estimated along with the corresponding transfer function coefficients adequate optimization procedures need to be used.

3. IPMC: Physics and Experimental Configuration

3.1. Working Principles and Manufacturing. IPMC consists of a fluorocarbon membrane containing sulfonate groups covered on both sides with a thin noble metal coating layer. The IPMC actuator sample is manufactured with three primary coatings and one secondary coating of platinum. To increase platinum deposition the dispersing agent polyvinylpyrrolidone (PVP) has been used with a concentration of 0.001 M [2]. The core of device is based on *Nafion*, distributed by *DuPont*; the characteristics of such an ionic polymer working in a humid environment allow the IPMC to work as actuator. The liquid molecules (generally water) which are mobile in the polymer structure, in fact, are at the basis for the electrochemical and mechanical transduction; they are driven by the voltage applied to the polymer via the metallic electrodes. The metal used to realize the device electrodes is usually platinum or gold.

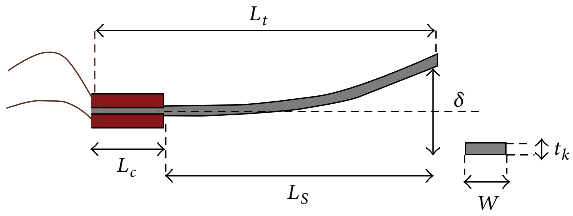

Figure 1: IPMC structure.

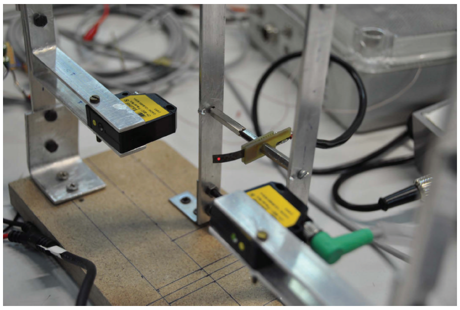

Figure 2: Experimental setup: mechanical structure, IPMC membrane, and laser beam.

3.2. Experimental Setup. The IPMC model was developed considering a configuration of a beam clamped at one end, as schematized in Figure 1. The pinned end is also used to apply the electrical stimulus via the electrodes.

The geometric parameters of the IPMC sample, as reported in Figure 1, are $L_S = 28$ mm, $L_C = 6$ mm, $t_k = 200\,\mu$m, and $W = 5$ mm.

While the input signals V_{in} were applied to the IPMC electrodes, the free deformation δ has been measured through a laser distance sensor, *Baumer Electric OADM* 12.

In order to determine the IPMC frequency response, sinusoidal inputs at different frequencies have been applied.

The considered range is between 50 mHz and 50 Hz with an amplitude of 3 Vpp, and the following set of frequencies has been applied:

$$\begin{aligned} \text{frequency} = [&0.05 \quad 0.1 \quad 0.4 \quad 0.7 \quad 1 \quad 3 \quad 7 \quad 10 \quad 13 \\ &17 \quad 20 \quad 22 \quad 25 \quad 27 \quad 30 \quad 31 \quad 32 \quad 33 \\ &34 \quad 35 \quad 36 \quad 37 \quad 38 \quad 40 \quad 43 \quad 47 \quad 50]. \end{aligned} \tag{5}$$

Three acquisition sets have been considered, in the following referred as Acq_1, Acq_2, and Acq_3.

Figure 3 shows the magnitude and the phases of the acquired signals. The three measurement sets have been successively acquired starting from the lower frequency towards the higher one and then back to the lower one.

The sampling frequency is the same for all the sinusoidal inputs and is equal to 1100 Hz.

The mechanical structure gripping the IPMC membrane and the measurement laser are shown in Figure 2.

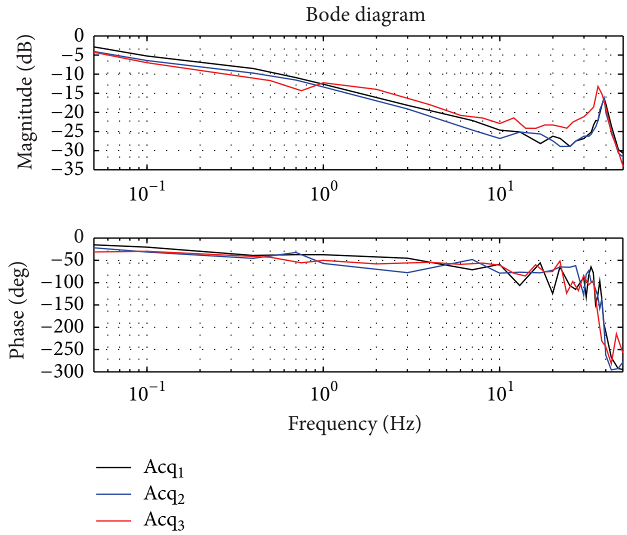

Figure 3: Magnitude and phase for the three acquisition sets.

4. Fractional Order Transfer Function Modeling

The acquired data shows a second-order like frequency response; see Figure 3. It is possible to note that, at low frequency, both the magnitude and the phase of the Bode diagram show a trend of fractional order.

It is possible to view that the magnitude curve slope is lower than 20 db/dec, and the phase does not follow integer order variations.

The high-frequency noise that affects the frequency response is due to the low quality of the measured signals, and it mainly affects the phase representation.

These considerations suggest considering a fractional order model. The following building blocks for the FOTF have been therefore considered:

(i) $G_1(s) = k/s^{\alpha}$

(ii) $G_2(s) = 1/(1 + \tau s^{\alpha 1})$

(iii) $G_3(s) = w_n^2/(s^2 + 2\xi w_n s + w_n^2)^{\alpha 2}$.

The first term allows to model a fractional pole at $s = 0$, the second one a fractional order pole with time constant τ, and the third one a second order fractional order term with a pair of complex poles.

The structure of the complete model for the FOTF if assumed is as follows:

$$G(s) = G_1(s)\, G_2(s)\, G_3(s). \tag{6}$$

Applications of IPMC as actuators imply the availability of a good model at low frequency.

The model representation in (6) proves to be a more accurate model at low frequencies with respect to the one presented in [12].

Taking into account the sets of available measurements, four different frequency models have been determined.

Table 1: FOTF parameters GAs optimized.

	k	α	τ	α_1	α_2	w_n	ξ	Error
Model_1 on Acq_1 data	3.000	0.181	0.766	0.783	1.281	40.273	0.079	21.38%
Model_2 on Acq_2 data	4.21	0.184	1.216	0.695	1.320	39.233	0.079	21.53%
Model_3 on Acq_3 data	1.878	0.268	0.392	0.663	1.261	37.876	0.120	22.18%
Mean error model	6.756	0.225	0.847	0.668	1.401	39.867	0.110	21.11%

Table 2: FOTF parameters simplex optimized.

	k	α	τ	α_1	α_2	w_n	ξ	Error
Model_1 on Acq_1 data	0.693	0.330	0.257	0.810	1.132	40.064	0.059	21.81%
Model_2 on Acq_2 data	1.374	0.300	0.499	0.700	1.222	39.175	0.066	21.45%
Model_3 on Acq_3 data	2.835	0.225	0.587	0.612	1.300	36.916	0.107	23.25%
Mean error model	0.482	0.376	0.196	0.798	1.101	39.536	0.055	22.82%

The first three are obtained from the measurement sets Acq_i, while the fourth one is determined as a model with a mean error computed over the three measurement sets.

The parameters of the transfer function $G(s)$ that are k, α, τ, α_1, α_2, w_n, and ξ have been determined applying both the simplex method and GAs.

The object function applied during the optimization procedures takes into account both the module and the phase of the FOTF and consists in the sum of two terms:

$$\text{OBJ1} = \frac{\sqrt{\sum (G_{\text{meas}} - G_{\text{sim}})^2}}{\sqrt{\sum G_{\text{meas}}^2}}, \tag{7}$$

where G_{meas} is the gain of the measured signal and G_{sim} is the module of the simulated one.

And the second term takes into account the phase

$$\text{OBJ2} = \frac{\sqrt{\sum (\text{Ph}_{\text{meas}} - \text{Ph}_{\text{sim}})^2}}{\sqrt{\sum \text{Ph}_{\text{meas}}^2}}, \tag{8}$$

where Ph_{meas} is the phase of the measured signal and Ph_{sim} is the phase of the simulated one.

Tables 1 and 2 report the results related to the FOTF parameters identification applying GAs and simplex method, respectively.

The Bode diagrams of the obtained FOTF are given in Figures 4, 5, 6, 7, 8, 9, 10, and 11.

Figures 4–7 show the frequency responses obtained via GAs while Figures 8–11 via simplex method.

According to the error provided in Tables 1 and 2 both the optimization procedures provide a good frequency matching.

It is worth noticing that the models obtained via GAs (Figures 4–7) provide a better fitting at low frequencies.

5. Conclusion

The paper proposes an enhanced fractional order transfer function model of an IPMC membrane working as actuator. The IPMC model has been determined exploiting experimental data.

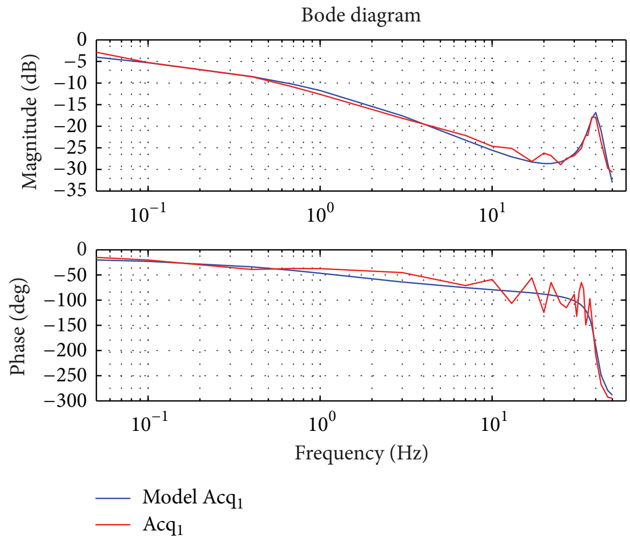

Figure 4: Magnitude and phase of the model on Acq_1 data via GAs.

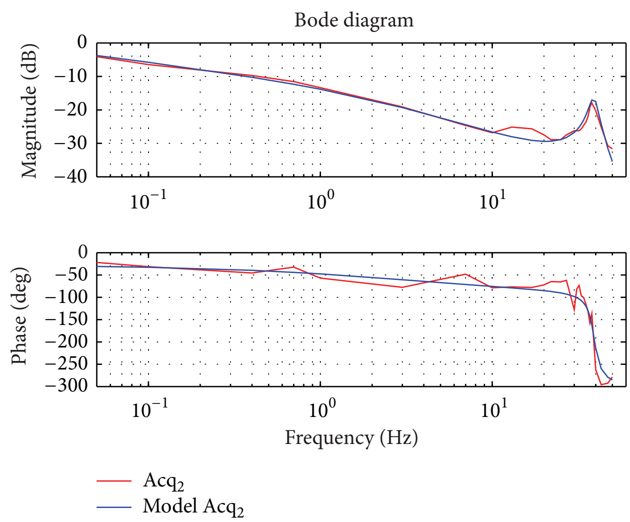

Figure 5: Magnitude and phase of the model on Acq_2 data via GAs.

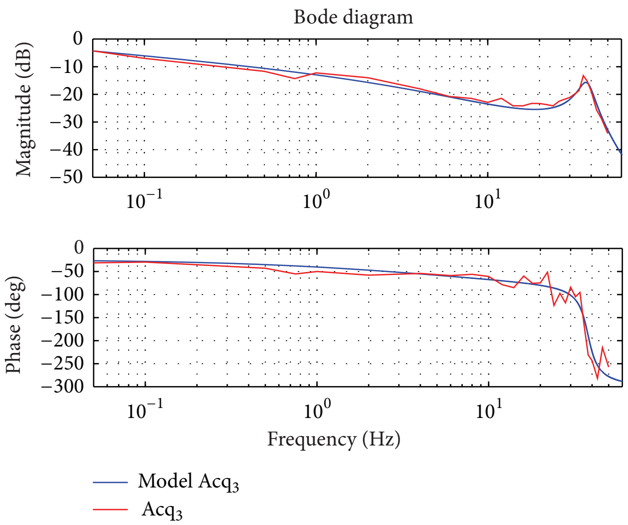

FIGURE 6: Magnitude and phase of the model on Acq_3 data via GAs.

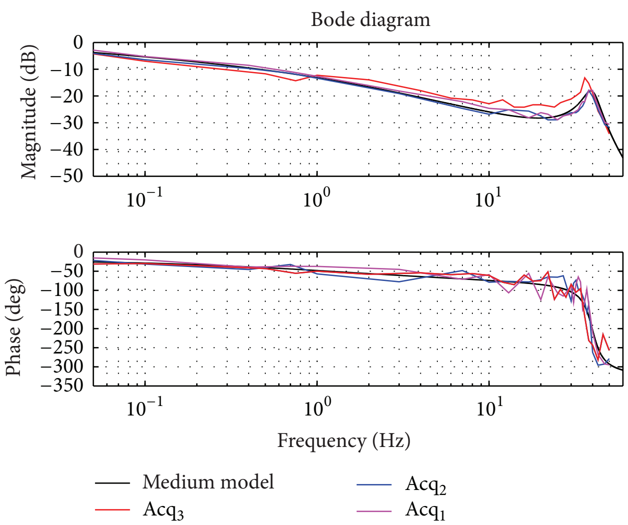

FIGURE 7: Magnitude and phase of the mean model on Acq_1, Acq_2, and Acq_3 via GAs.

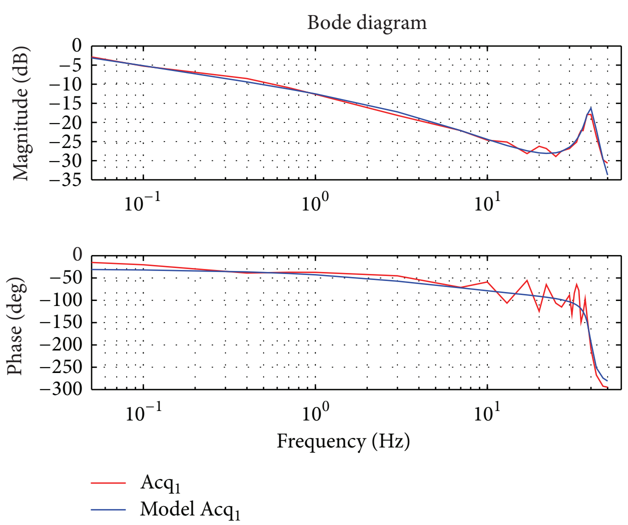

FIGURE 8: Magnitude and phase of the model on Acq_1 data via simplex method.

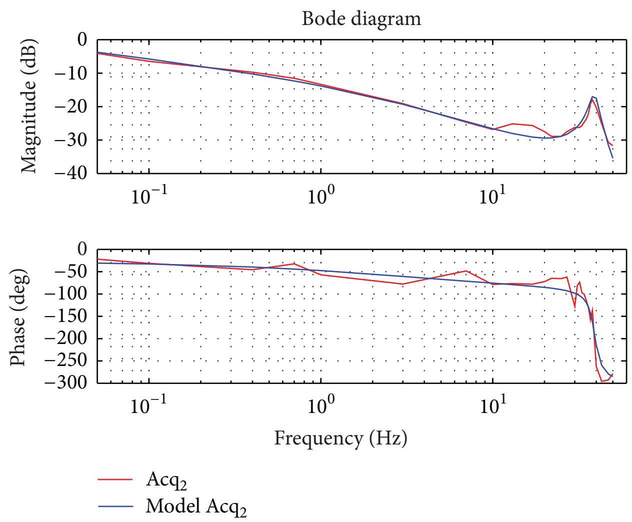

FIGURE 9: Magnitude and phase of the model on Acq_2 data via simplex method.

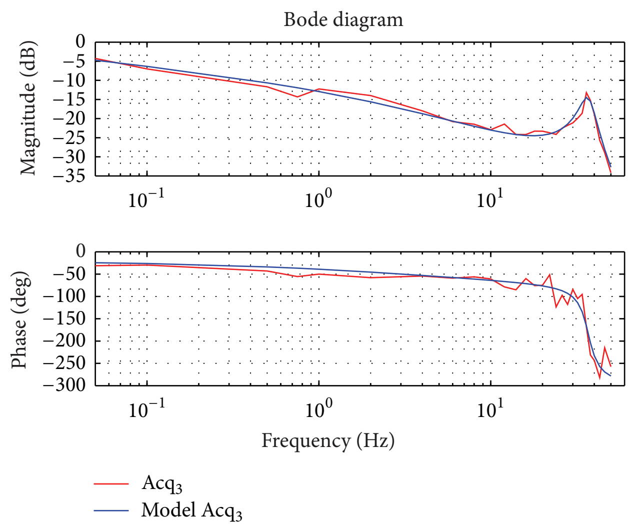

FIGURE 10: Magnitude and phase of the model on Acq_3 data via simplex method.

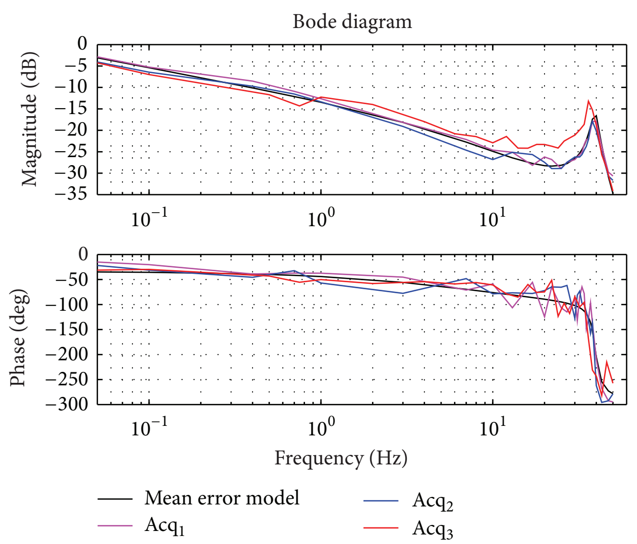

FIGURE 11: Magnitude and phase of the mean model on Acq_1, Acq_2, and Acq_3 via simplex method.

The model was proven to be very accurate at low frequencies, and such frequency matching makes it suitable for control system design.

Acknowledgment

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