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A GENETIC ALGORITHM APPROACH FOR MODEL REFERENCE ADAPTIVE CONTROL OF IONIC POLYMER METAL COMPOSITES

Brijesh C. Lavu
Measurement and Control Engineering Research Center
Idaho State University
Pocatello, ID, 83209, USA
lavubrij@isu.edu

Marco P. Schoen
Measurement and Control Engineering Research Center
Idaho State University
Pocatello, ID, 83209, USA
schomarc@isu.edu

Ajay Mahajan
Department of Mechanical Engineering and Energy Processes
Southern Illinois University
Carbondale, IL, 62901, USA
mahajan@engr.siu.edu

Abstract – **Electroactive polymers undergo physical deformation to external voltage stimuli. These electrically activated polymers possess extraordinary features making them capable as lightweight sensors and actuators in manifold applications. The characteristics of applied voltage and environmental conditions, especially the moisture content surrounding the polymer, have a combined influence on the dynamical behavior of these polymers. In order to characterize these polymers under varying environmental conditions, this paper discusses the experimental procedure and modeling techniques used to derive a representative model. Ionic polymer metal composite polymers are used for this humidity relative electrodynamical study. Insight on the numerous applications of electroactive polymers as actuators and the built model enabled a controller is designed for a typical tracking problem. The control architecture includes a Model reference adaptive scheme along with pole-placement control strategies to achieve the goal of tracking. A genetic algorithm approach is implemented to carryout an optimized control action. Tracking control of ionic polymer metal composites as actuator resembling that of a real-world scenario is simulated and reveals promising results.**

I. INTRODUCTION

Over the past decade, research works pertaining to the behavior and usage of electro active polymer (EAP) materials have shown promising results. EAPs are a special kind of polymer material that responds to electrical stimuli by exhibiting large, bending movements. Some of the significant qualities of the EAPs are high resilience, low density, large induced strains etc. [1]. These properties elevate EAPs to provide a cutting-edge technological revolution in a wide spectrum of applications. For instance, these so-called EAPs are potentially useful in constructing MEMS, artificial muscles, androids, sensors/actuators, miniature creature replicas, as well as in multidisciplinary areas such as the biomedical, entertainment, and space industries. This paper will focus on a particular kind of EAP, called the Ionic Polymer Metal Composites (IPMC).

A typical IPMC has a thin (200μm) perfluorinated ion exchanged base polymer membrane with metal electrodes (5-10 μm) fused on either side. As part of the manufacturing process, this base polymer is further chemically coated with metal ions that comprise the metallic composites. An IPMC usually is kept in a hydrated state to ensure proper dynamical operation. In such an aqueous state, it exhibits large bending strains when imposed to low electric stimuli (1-5V). This physical deformation is due to the diffusion of the mobile counter-ions towards one of the electrodes on the application of coulomb forces [2], [3], [4].

The lack of movable parts, modest actuation potentials, requirements integrated with features like toughness, large actuation strain, robustness, and durability promises that IPMC could enhance traditional actuator designs [4], [5].

Several results regarding the usage and performance of IPMCs were recently reported [1], [3], [6]-[13]. The complexity and irregularities associated with the modeling of IPMCs has forbidden an accurate description of the electromechanical response of IPMC in the presence of environmental changes. This paper provides an analysis of the influence of one of these environmental factors to IPMCs. In particular, the influence of relative humidity (RH) surrounding the IPMC on the dynamical performance is investigated. From the characterization of the IPMC's electromechanical behavior, a state space model is devised. Finally, based on the derived model, a controller is proposed that includes a variation of a model reference adaptive structure and an optimal scheme that includes a Genetic Algorithm (GA) approach. This designed controller is then implemented for the problem of tracking control of the IPMC.

Section II describes the experimental set-up, identification and modeling performed in composing the IPMC model; Section III dwells on the proposed Model reference adaptive control (MRAC) scheme and utilization of genetic algorithm as a tool for the tracking control of IPMC actuator, and finally, Section IV gives insight over the simulated controller results with various interacting elements.

II. SYSTEM MODELING

In order to correlate the polymer workspace's RH level on its operation, an experimental set-up was used. The model extraction steps included system identification, model reduction, and polynomial model fitting for state-space models.

A. Experimental Procedure

The experimental setup shown in Fig. 1 was used for observing the dynamic responses of IPMC test sample at various artificially established operating RH levels.

As shown in Fig. 1, IPMC test samples were clamped appropriately and enclosed in an airtight acrylic chamber that is internally maintained at a particular RH value.

Various salt solutions were used to control the required distinct humidity conditions inside the chamber [14]. The salt solutions inside the air-sealed chamber were kept in equilibrium for 48-72 hours prior to each experimental run. A hygrometer tightly fitted into the chamber, as shown in Fig. 1, monitors the RH levels and temperature of the chamber at all times. A CCD camera positioned in line-of-sight of the IPMC polymer captures all movement during the entire phase of the experiment. Two computers equipped with data acquisition systems intermingled with a power amplifier (120W, 5A) provide the necessary controlled activation signals to the test polymer samples and keeps a log of the IPMCs response, due to these stimuli signals.

A number of experiments were conducted at various magnitudes of RH in the range of 72.9%-98.25%. The magnitude levels and time interval of the excitation signals fed to the IPMC samples were kept random in the range of -1.5 to +1.5 volts amplitude and 0.75 to 4.75 seconds duration respectively. Each experiment included a collection of 6000 data points. The CCD camera operating at 30 frames per second acts as the sensor capturing each side view deflection of the polymer during the experiment in the form of a monochrome video.

The videos are processed using image-analysis algorithms to extract the loci of the polymer strip in correspondence to the voltage input. The image processing included edge-detection, evaluation of the median axis, and estimation of the locus of intermittent points on the evaluated median axis. The image acquisition used a pre-determined pixel to millimeter conversion calibration. Fig. 2 shows a frame of such a captured moisture-enriched IPMC sample in motion used in the image-analysis procedure, where t_1 and t_2 represent the vertical distances of the upper and lower edges of the polymer respectively from the top horizontal reference line. These vertical distances are then utilized to compute the median axis of the polymer.

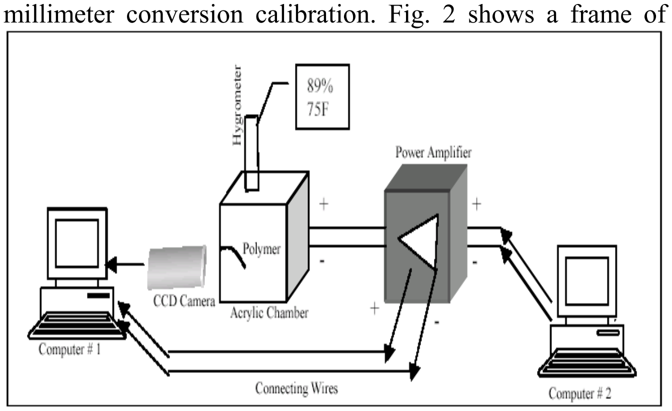

Fig. 1 Schematic of the actual experimental setup

The computed displacements of the points lying on the median axis of the IPMC in association with their respective input voltages are then used for the system identification algorithm.

An optimal point lying on the median axis of the polymer was considered for modeling purposes. This was chosen to reduce the complexity of the overall model and an application that demands a single-point modeling. Moreover, although all experiments were conducted at room temperature, each experiment's operating temperature slightly differed from the other. These slight temperatures variation on the overall IPMC modeling were neglected.

B. System Identification

The motivation of using system identification (SI) for modeling lies in the complexity of deriving a representative model for varying humidity levels based on physical laws. SI allows us to infer a dynamical model based on the collected input output data. Parametric system identification methods that utilize an open-loop structure were used. The underlying assumption for this is the system to be identified is linear around the operating point and time invariant during the phase of the identification experiment. An Observer Kalman filter identification (OKID) method was employed. OKID uses a parametric model structure, such as the Autoregressive with exogenous input (ARX) model and some estimation scheme that allows us to estimate the model parameters from a constructed information matrix. These parameters are then used to extract the Markov parameters, which are utilized in an Eigensystem Realization algorithm (ERA) to find the respective state-space model of the identified system. Since the input signal was comprised of random step inputs, a numerical differentiation was used as in (1).

$$idp_n = \frac{edp_{n+1} - edp_n}{0.0333} \qquad (1)$$

where, idp is the impulse data point, edp is the experimental data point and n is a data point number .

Later the SI algorithm based on [16] were implied in Matlab® for carrying out the identification process on the refined experimental data.

The parameter values that were used for the implementation of SI are tabulated in Table I.

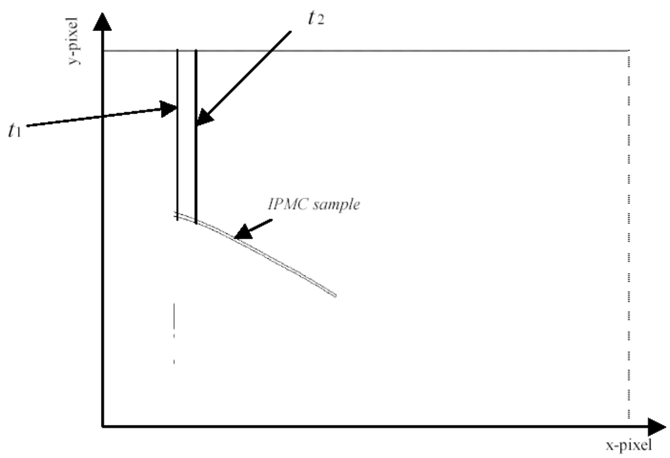

Fig. 2 Median axis identification of an edge detected polymer frame

TABLE I
LIST OF IMPLEMENTED SI PARAMETERS AND THEIR VALUES

SI Parameter	Value
Order of the used ARX model	100
Number of Markov parameters	275
Number of states to be realized	4

C. Model Formulation

The discrete state-space model sets yielded from SI for each of the experimental data, although distinct, relate to the same point on the IPMC polymer. Hence, in order to deduce a general model based on these inferred model sets, four model sets identified at RH levels of 72.9%, 79%, 93.3% and 98.25% were chosen. Polynomial curve fitting techniques giving minimum interpolation errors are used on the entries of the system matrices of the 4 selected models. Fig. 3 exemplifies the curve fitting of the eigenvalues of the four models. Modal diagonalization and design of transformation matrix value techniques [17] based on observations are also used.

The derived polynomial state-space model describing the electromechanical behavior of the IPMC as a function of RH level, ultimately, is given in the appendix.

III. CONTROLLER DESIGN

The potential of numerous applications of the IPMC material poses the question of how to control such materials. Quite often, the goal of a controller design for IPMC is to achieve the tracking of some point on the IPMC along a predefined path, i.e. as actuators or final control elements for optical elements. It is to be noted that IPMC actuators are often subjected to varying environmental conditions, especially the RH factor to which it is highly sensitive. To cope with such unpredictable variations, a controller should adapt to the new conditions accordingly for proper control action.

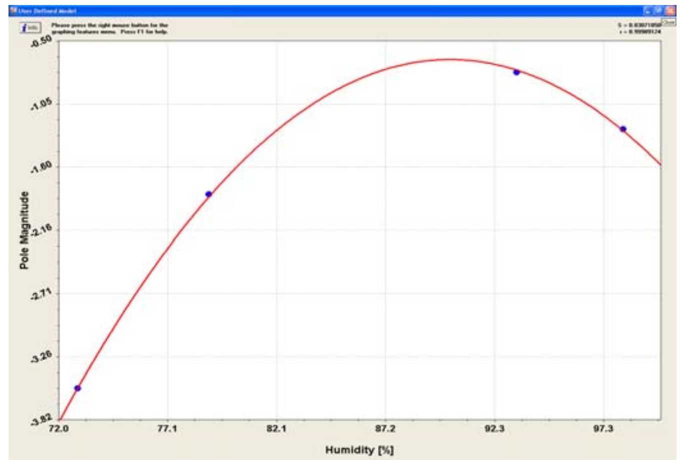

Fig. 3 Plot of polynomial curve fitting the dominant poles of the models at 72.9%, 79%, 93.3% and 98.25%

A. Control Scheme

Since the controller parameters have to be reset on every iteration as part of the adaptation requirements, a model reference adaptive control (MRAC) scheme best suits the design purpose. The general model of IPMC derived in Section II serves as the reference model in this proposed control scheme. Any changes in the to-be-controlled IPMC actuator is reflected in the reference model, thereby further manipulating the controller mechanisms. This is a special and seldom case of MRAC where the reference model itself is a time variant instead of a normal constant one.

B. Controller Design

The controller block in the MRAC scheme is implemented by the "pole-placement" technique. This technique is simple and allows the allocation of poles of a close-loop system to be placed anywhere in the s -plane, based on the controllability to achieve the desired system performance. The closed-loop tracking control of the IPMC is a SISO system, which can be mathematically expressed as,

$$\begin{aligned} x_{n+1} &= Ax_n + Bu_n \\ y_n &= Cx_n + Du_n \end{aligned} \tag{2}$$

where A, B, C and D are the discrete-time state-space system matrices of IPMC actuator. The pole-placement method transforms (2) into

$$\begin{aligned} x_{n+1} &= A_c x_n + Bu_n \\ y_n &= Cx_n + Du_n \end{aligned} \tag{3}$$

where,

$$A_c = A - BG \tag{4}$$

and 'G'is the system gain matrix. In general, G is a row vector of the order equal to the number of poles of the IPMC actuator system.

The objective of the controller is to estimate the gain matrix G for the then presented parameters for emitting a control action. For this core objective, a genetic algorithm is used as a tool.

C. Genetic Algorithm

Genetic algorithms are evolutionary inspired search and optimization methodologies. The premise is not only to find the parameters of the gain matrix G using GA, but also to minimize a performance criterion and to satisfy the control requirements specified. The performance criteria associated with these intelligent algorithms in search of entries of G is called the "objective function" in genetic algorithms terminology. Equation (5) expresses the objective function used for the GA computations.

$$COST = \int_{t_0}^{t_f} [(os + st + E) + Kdy]dt \qquad (5)$$

where,
os , refers to the system's maximum overshoot
st , refers to the system's settling time
E , refers to system's total energy
K , a penalizing factor
dy , refers to tracking error and
t_0, t_f , refers to the initial and final times (taken as 0 and 10 seconds respectively)

The design of the above cost function intends to build a gain matrix that provides minimum overshoot, settling time, energy, and tracking error over duration of 10 seconds for the required tracking control. Fig. 4 presents the scheme of the entire working principle of GA.

The GA was implemented in Matlab® with the parameter settings as listed in Table II.

D. Control Loop

Fig. 5 depicts the control loop that simulates a tracking control problem of the IPMC based on the above discussion. It can be viewed from the control-loop that, in addition to the general MRAC elements, other supplementary elements are interlinked to mimic the real-world IPMC actuator control as close as possible. Table III lists the supplementary elements and their respective function.

TABLE II
LIST OF GA PARAMETER VALUES USED FOR SIMULATIONS

GA Parameter	Value
Model order	4
Number of iterations/generations	80
Initial population size	96
Population size for the following generations (1-80)	48
Number of chromosomes selected for mating	24
Total number of parameters in chromosome	4
Mutation rate	4%
Higher limit value for chromosome selection	1000
Lower limit value for chromosome selection	-1000
Penalizing factor in cost function	20

TABLE III
SUPPLEMENTARY ELEMENTS AND THEIR FUNCTIONS

Element	Function
Transducer	Determines the magnitude of the activation voltage signal (IPMC inverse model)
Voltage Logger	Keeps log of the voltage states
Smart Transducer(Stransducer)	Same as TransducerBlock and to prevent noise accumulation
Humidity meter	Simulates a humidity sensor
Noise	Generates noise into plant
EnviroHumidity	Generates RH changes in the plant

Equation (6) represents the transfer function of the humidity meter having 80 seconds response time, while (7) is used to simulate sinusoidally varying RH environment in the range of 90%-98%.

$$H = \frac{PH}{1+80s} \qquad (6)$$

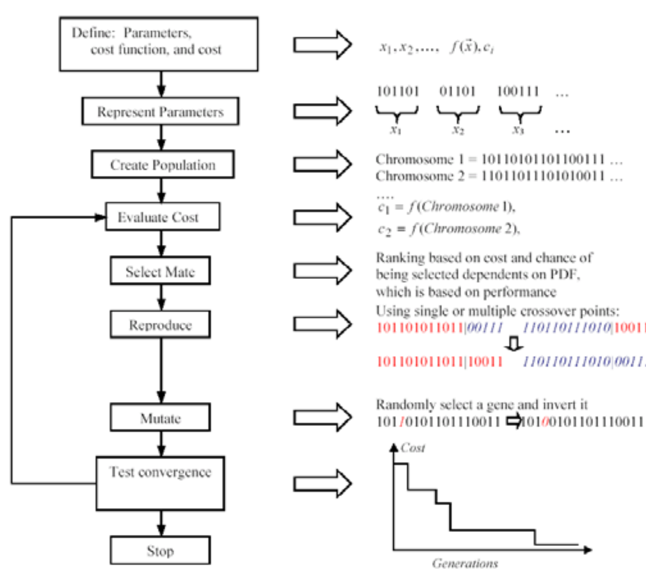

Fig. 4 Working principle of Genetic algorithm

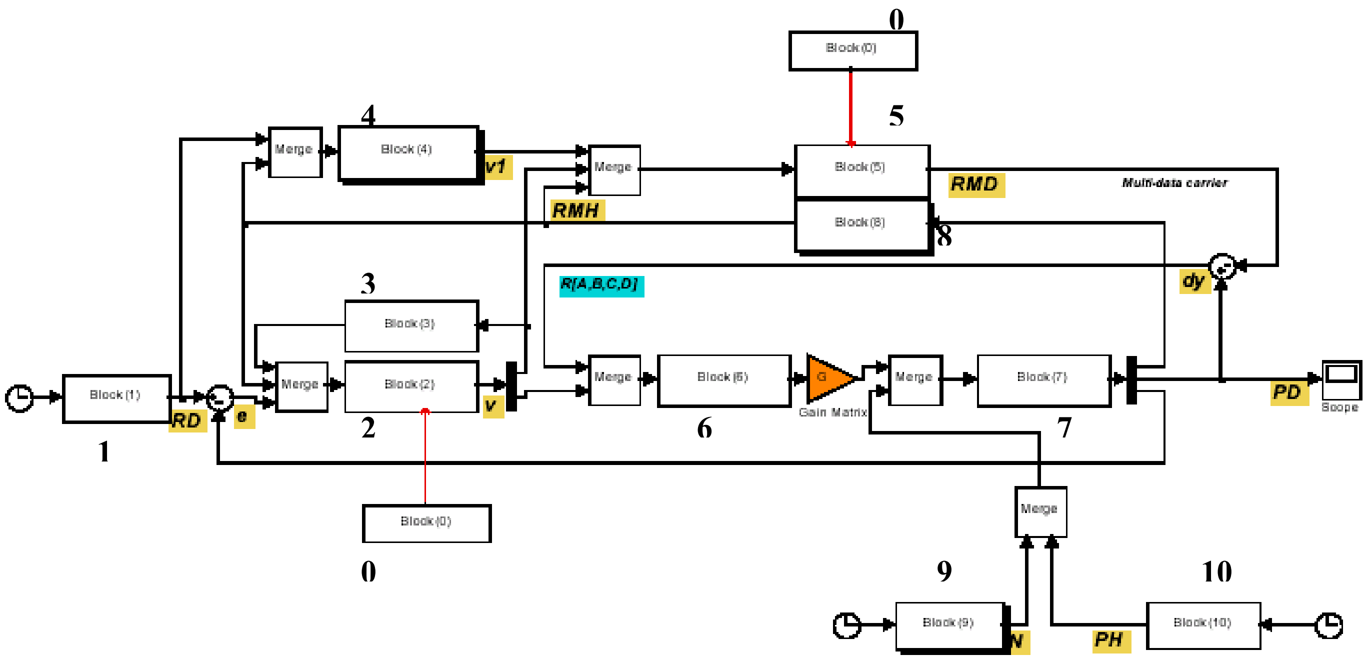

Fig. 5 Schematic of the closed-loop tracking control of IPMC actuator. Blocks: 0. Initial conditions 1. Required Tracking 2. Transducer 3. Voltage Logger 4. Smart Transducer 5. Reference model 6. Controller 7. IPMC Actuator 8. Humidity meter 9. Noise 10. EnviroHumidity

where, H is the humidity meter output (%) and PH is the plant relative humidity (%).

$$PH = 4\sin\left\{\left(\frac{t}{2\pi 3.25}\right) + 60\right\} + 94 \qquad (7)$$

where, PH is the generated plant relative humidity (%) and t is the time period (seconds).

IV. SIMULATION RESULTS

Simulation results of the controller tracking performance implemented through the above closed-loop control system are shown in the following Figs. 6 to 11.

A. Results Analysis

From the plots, it can be interpreted that the use of genetic algorithms for tracking control of IPMC under subjected noise and RH changes achieve good tracking results. From Figs. 6 and 7 the correlation factor between the desired and simulated tracking was found to be 99.15% and the root mean square error was estimated as 0.2866, respectively. These statistical, measured values of the tracking performance deduce that genetic algorithm in conjunction with MRAC for the control of IPMC is possible and leads to good results. The spikes in Fig. 7 reflect the sudden input step changes. However, from Fig. 10 it can be analyzed that, although the sensitivity of the cost function is much less, it can be enhanced by either increasing the number of genetic algorithm iterations or by increasing the penalizing factor K value in (5).

V. CONCLUSIONS

An IPMC dynamical characterization incorporating the effects of RH has been carried out via experimental work. Furthermore, a controller has been designed for tracking control of IPMC actuator. The controller in a model reference adaptive scheme is implemented, utilizing genetic algorithm method, achieving good tracking results of IPMC actuators.

VI. ACKNOWLEDGEMENTS

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Fig. 6 Desired and simulated tracking(cm)

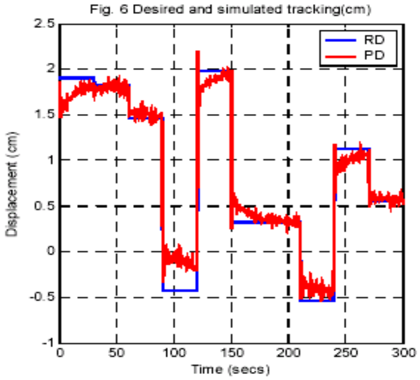


Fig. 7 Tracking Error

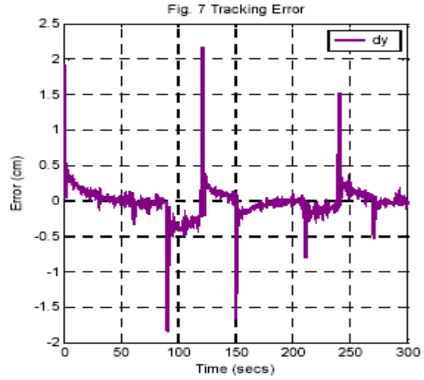


Fig. 8 Reference model tracking(cm)

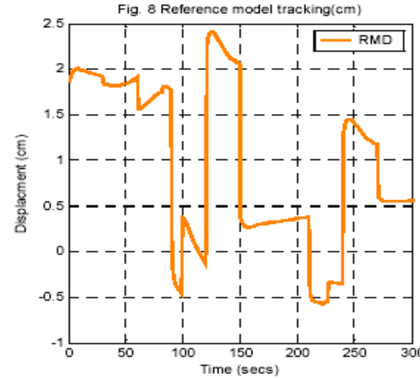


Fig. 9 Voltage Waveforms(volts)

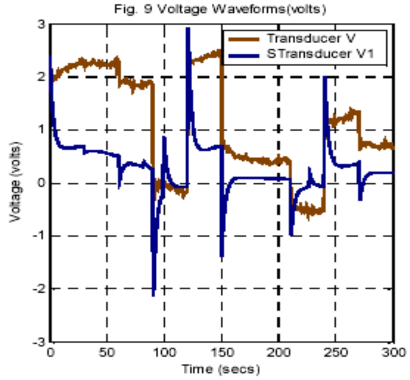


Fig. 10 Minimum Fitness Value

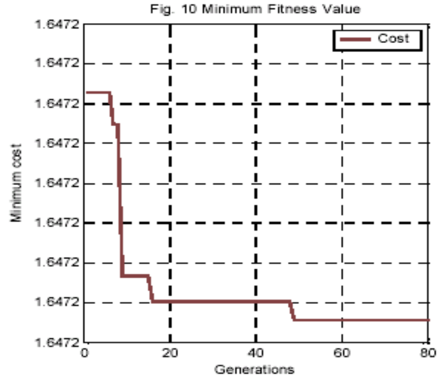
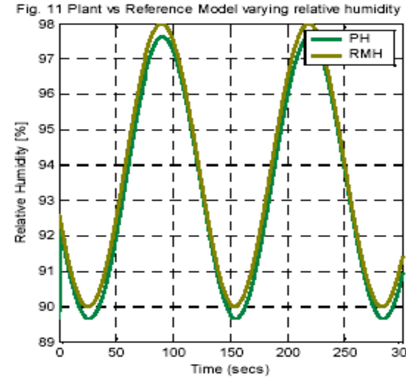


Fig. 11 Plant vs Reference Model varying relative humidity levels



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APPENDIX

<u>IPMC continuous model</u>

$$\tilde{A}=\begin{pmatrix} a_{11} & a_{12} & 0 & 0 \\ -a_{21} & a_{22} & 0 & 0 \\ 0 & 0 & a_{33} & 0 \\ 0 & 0 & 0 & a_{44} \end{pmatrix}; \qquad \tilde{B}=\begin{pmatrix} b_{11} \\ b_{21} \\ b_{31} \\ b_{41} \end{pmatrix};$$

$$\tilde{C}=\begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} \end{pmatrix}; \qquad \tilde{D}=0.8$$

where

$$a_{11}=a_{22}=-0.0032hum^2+0.3808hum-10.9610$$
$$a_{12}=a_{21}=-0.1000hum^2+23.7000hum-1003.5000$$
$$a_{33}=0.0028hum^2-0.3450hum+5.6500$$
$$a_{44}=0.0045hum^2-0.4255hum-3.8214$$
$$b_{11}=0.0384hum^2-6.9394hum+315.9648$$
$$b_{21}=-0.0245hum^2+4.0873hum-168.0343$$
$$b_{31}=-0.0243hum^2+4.8396hum-227.7524$$
$$b_{41}=-0.0531hum^2+8.9851hum-374.3626$$

and

$$c_{11}=0.0019hum^2-0.3296hum+14.5295$$
$$c_{12}=0.0006hum^2-0.0917hum+3.7350$$
$$c_{13}=0.0001hum^2-0.0281hum+1.2142$$
$$c_{14}=0.0007hum^2-0.1236hum+5.3624$$

In above *hum* is the relative humidity level[%].