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6. AUTHOR(S)
Dr. Eyad H. Abed

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Systems Research
and Dept. of Electrical and Computer Engineering
University of Maryland
College Park, MD 20742

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This is the final report for AFOSR Grant Number F49620-96-1-0161, "Active Control of Surge and Stall in Axial Flow Compressors." The research effort under this grant focused on combined monitoring and control of stall phenomena in axial flow compressors. The cognizant AFOSR Program Manager for the grant was Dr. Marc Jacobs, of the Directorate of Mathematical and Information Sciences and Computational Mathematics. The Principal Investigator on the grant was Dr. Eyad Abed, a Professor in the Department of Electrical and Computer Engineering who holds a joint appointment with the Institute for Systems Research. The technical report begins with a summary of the main goals of the project. Next, the main achievements are discussed. The remainder of the technical report gives information including personnel supported under the grant, publications benefiting from the grant, interactions and transitions, and honors and awards received by the co-Pis during the term of the grant.

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Final Technical Report
for AFOSR Grant Number F49620-96-1-0161

Active Stall Control Mutlistage Compression Systems

Eyad H. Abed, Principal Investigator
Institute for Systems Research
and Dept. of Electrical and Computer Engineering
University of Maryland, College Park, MD 20742
abed@eng.umd.edu

Submitted to:
Dr. Marc Q. Jacobs
Program Manager
Dynamics and Control
and Computational Mathematics
Directorate of Mathematical and Information Sciences
AFOSR/NM
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

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OUTLINE

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2. Accomplishments/New Findings
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4. Publications
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6. Honors/Awards

FINAL TECHNICAL REPORT

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The technical report begins with a summary of the main goals of the project. Next, the main achievements are discussed. The remainder of the technical report gives information including personnel supported under the grant, publications benefiting from the grant, interactions and transitions, and honors and awards received by the co-PIs during the term of the grant.

1 Overview of the Research Effort

The goals of the research effort are summarized as follows.

(i) *Precursors as warning signals for impending nonlinear instabilities.* This aspect of the research involves a re-examination of the theory of noisy precursors of bifurcations developed by Wiesenfeld and co-workers with the new perspective that the precursors be viewed as warning signals for loss of stability of nonlinear systems. Originally, the noisy precursors concept was introduced as a feature of bifurcations that could be used for purposes of ampplification. The theory was developed for systems operating near limit cycles. Extension of the concepts to systems operating near equilibrium points was a preliminary goal of the research. Emphasis was placed on Hopf and stationary bifurcations, both subcritical and supercritical.

(ii) *Closed-loop monitoring systems for detecting impending instabilities using precursors.* A main goal of the research was to build on the notion of noisy precursors to develop automatic monitoring systems for detecting impending instabilities. The purpose of these systems is to detect with enhanced accuracy instabilities of various frequencies, and to facilitate combined monitoring and control of instabilities. For the latter purpose, bifurcation control calculation techniques are applied to the closed-loop monitoring systems to ensure safe transition should an instability arise.

(iii) *Application of monitoring systems to multistage compression systems.* This goal of the research effort involves application of the closed-loop monitoring system designs of (ii) to nonlinear axial flow compression system models. The result is a re-design of nonlinear stabilizing controllers for axial flow compressors to yield combined monitoring and control systems for alleviation of stall phenomena.

(iv) *Further development of active stall control laws.* Active stall control laws based on bifurcation analysis were developed under prior AFOSR funding and have influenced a significant number of subsequent research efforts. Two aspects of the bifurcation-based controllers that required further work were addressed in this phase of the research project. The first involves improving the achieved pressur rise over a significant range of operating conditions past the stall point. The second involves mitigation of oscillations linked to surge that can arise shortly after instability on the stabilized bifurcated equilibrium branch.

(v) *Sensor and actuator placement for active stall control.* The closed-loop monitoring systems developed in the research employ noise inputs (either naturally occuring or injected) that excite warning features in measured outputs. This phase of the research aims at enhancing the strength of the warning signal by judicious placement of sensors and actuators. The work employs participation factors, a tool for determining the contribution of modes in states (and vice versa) in linear systems.

2 Accomplishments/New Findings

The main accomplishments of the research project can be divided into results on

- general instability monitoring system design based on noisy precursors of bifurcations;

- closed-loop monitoring of stall in axial flow compression system models;
- new active stall control designs for improved performance over a broad parameter range;
- generalized input/output participation factors for actuator and sensor placement in system monitoring for impending instability detection, and for quantitative monitoring of dominant system modes;
- investigation of detectability of direction of bifurcation from input/output measurements prior to instability.

Note that the research results cover the desired goals as well as some additional achievements that were added to the tasks during the course of the work. For instance, application of signal processing tools for monitoring of dominant system modes was not part of the original set of goals.

In the following, we elaborate on the main accomplishments of the research project, making reference to published work for details.

1) We extended the noisy precursor theory of Wiesenfeld and co-workers from systems operating along limit cycles to systems

$$\dot{x} = f(x, \mu) + w(t) \tag{1}$$

operating near equilibrium points (instead of limit cycles). Here, $x \in R^n$, μ is a bifurcation parameter, and $w(t) \in R^n$ is a zero-mean vector white Gaussian noise process.

We showed that one can observe a growing peak in the power spectrum of a measured output of a nonlinear system with white Gaussian noise input as the system approaches a bifurcation [1]-[3],[5]-[7]. In the case of Hopf bifurcation, the location of the power spectrum peak coincides with the imaginary axis crossing frequency of the critical eigenvalues. In the case of stationary bifurcation the power spectrum peak occurs at zero frequency. Peaks near zero frequency require a very long time record to resolve. Peaks at high frequency require fast sampling. Thus, we developed closed-loop monitoring systems that shift the expected peak to a desired frequency value.

2) An open-loop stability monitoring scheme based on noisy precursors would involve monitoring the power spectrum of a measured output to detect growing peaks. If such a peak is detected, with asymptotics agreeing with predictions of the theory, a loss of stability at the corresponding frequency would be predicted. There are several difficulties with such an open-loop approach. A main weakness is the requirement for excessive measurement intervals for detection of stationary bifurcations (since they occur at zero frequency). Another weakness is the lack of any control over the frequency at which a precursor peak occurs, leading to a need for continuous monitoring throughout a large frequency band. Finally, an open-loop monitoring scheme cannot be easily combined with a control logic for mitigating the effects of possible bifurcations. To address these issues, we developed a basic closed-loop monitoring system.

The most basic closed-loop monitoring system we developed [1]-[3],[5]-[7] addressing the noise-driven system (1) is

$$\begin{aligned} \dot{x}_i &= f(x,\mu) + w(t) - cy_i \\ \dot{y}_i &= cx_i \end{aligned} \tag{2}$$

Here, $y \in R^n$, $c \in R$ and $i = 1, 2, \ldots, n$. Note that the state vector consists of the original physical system states x augmented with the states y of the monitoring system. We proved the following result.

Proposition 1 *If the system (1) undergoes a pitchfork bifurcation from the origin at a critical parameter value $\mu = \mu_c$, then the augmented system (2) undergoes a Hopf bifurcation from the origin for the same parameter value. Moreover, if for any value of μ the origin of the original system (1) is asymptotically stable (resp. unstable), then the origin is asymptotically stable (resp. unstable) for the augmented system (2).*

The monitoring system above produces a Hopf bifurcation from a stationary bifurcation. However, the direction of the new bifurcation could differ from that of the original. For instance, a supercritical stationary bifurcation might result in a subcritical Hopf bifurcation. To address this problem, a modified monitoring system was proposed. It guarantees that the bifurcated limit cycle occurring in the augmented system is stable regardless of the stability of the stationary bifurcation occurring in the plant. The modification we introduced in the monitoring system involves the addition of a nonlinear term with a gain parameter that can be tuned to ensure the desired result:

$$\begin{aligned}\dot{x}_i &= f_i(x,\mu) + w(t) - cy_i \\ \dot{y}_i &= cx_i - mx_1^2 y_i \end{aligned} \tag{3}$$

Here, c and m are real constants. We showed that by choosing m positive and sufficiently large, we can ensure that the Hopf bifurcation is supercritical.

3) The closed-loop monitoring system designs mentioned above were applied to axial flow compression system models. Moore and Greitzer introduced the following third-order model of axial flow compressor dynamics:

$$\frac{dA}{dt} = \frac{\alpha}{\pi(m\alpha+1)}\int_0^{2\pi} C_{ss}(\Phi + A\sin\theta)\sin\theta d\theta \tag{4}$$

$$\frac{d\Phi}{dt} = -\frac{1}{l_c}\Psi + \frac{1}{2\pi l_c}\int_0^{2\pi} C_{ss}(\Phi + A\sin\theta)d\theta \tag{5}$$

$$\frac{d\Psi}{dt} = \frac{1}{4B^2 l_c}[\Phi - F(\gamma,\Psi)] \tag{6}$$

Here, A denotes the amplitude of the first harmonic mode of nonaxisymmetric flow; Φ is annulus-averaged (mean) gas-axial velocity; Ψ is the plenum to atmospheric pressure rise; θ is an angular coordinate along the circumference; C_{ss} and F are the compressor characteristic and inverse of the throttle characteristic function, respectively; α, l_c, and m are internal compressor lag, overall compressor length factor, and exit duct length factor, respectively; and B and γ are positive constants proportional to rotor speed and the throttle opening, respectively. We assume that the so-called throttle line F is strictly increasing in each of its variables.

Consider a nominal equilibrium point for which there is no asymmetric flow, i.e., let $A = 0$. Denote this equilibrium point by

$$x^0(\gamma) = \begin{bmatrix} 0 & \Phi^0(\gamma) & \Psi^0(\gamma) \end{bmatrix}^T \tag{7}$$

where $\Phi^0(\gamma)$ and $\Psi^0(\gamma)$ satisfy $\Phi^0 = F(\gamma, \Psi^0)$ and $\Psi^0 = C_{ss}(\Phi^0)$. At the parameter value $\gamma = \gamma^0$ for which $C'_{ss}(\Phi^0(\gamma)) = 0$, it is found that the Jacobian matrix has a zero eigenvalue and two eigenvalues with negative real part. This suggests that a stationary bifurcation occurs at $\gamma = \gamma^0$.

Based on these observations, we suggested a monitoring system for detection of incipient instability for axial flow compression systems. Since our monitoring system is based on state feedback which results in relocation of the measured output power spectrum peak and transformation of the bifurcation type, we need control inputs to the axial flow compressor. Hence, we will modify the axial flow compressor model to reflect the action of these control inputs.

Many ways are known for generating asymmetric flow in an axial compressor, such as oscillating inlet guide vanes, vanes with oscillating flaps, jet flaps, and tip bleed above the rotor. Paduano and co-workers implented control using a circumferential array of hot wires to sense propagating waves of axial velocity upstream of the compressor. Using this information, additional circumferential traveling waves were then generated with appropriate phase and amplitude by *wiggling* inlet guide vanes driven by individual actuators. Paduano and co-workers also used experiments to obtain a linear state space model which includes the effect of wiggling the inlet guide vanes.

No nonlinear model is available that includes the effect of dithering the inlet guide vanes. Therefore, we settled on using the following generic nonlinear model. Let the compression system with controlled inlet guide vanes be described by

$$\begin{aligned}
\frac{dA}{dt} &= \frac{\rho}{\pi}\int_0^{2\pi} C_{ss}(\Phi + A\sin\theta)\sin\theta d\theta + g_1(A,\Phi,\Psi)u && (8)\\
\frac{d\Phi}{dt} &= -\frac{1}{l_c}\Psi + \frac{1}{2\pi l_c}\int_0^{2\pi} C_{ss}(\Phi + A\sin\theta)d\theta + g_2(A,\Phi,\Psi)u && (9)\\
\frac{d\Psi}{dt} &= \frac{1}{4B^2 l_c}[\Phi - F(\gamma,\Psi)] + g_3(A,\Phi,\Psi)u && (10)
\end{aligned}$$

Here, we assume that effect of the input ($u \in R$) on the system can be modeled as affine. Note that we do not explicitly show any noise disturbance in (8)-(10). The influence of noise was, however, considered explicitly in the simulations.

We proved the following proposition.

Proposition 2 *Let g_1,g_2, and g_3 be general smooth functions with respect to each of their variables, and suppose g_1 does not depend on the bifurcation parameter. In addition, suppose that g_1 does not change sign along the equilibrium path as the parameter γ varies and its sign is known but not the exact function itself. Then the following augmented system with*

$u = -sign(g_1)\omega_1 y$ undergoes a Hopf bifurcation at γ^0:

$$\frac{dA}{dt} = \frac{\rho}{\pi}\int_0^{2\pi} C_{ss}(\Phi + A\sin\theta)\sin\theta d\theta + g_1(A,\Phi,\Psi)u \tag{11}$$

$$\frac{dy}{dt} = \omega_1 A \tag{12}$$

$$\frac{d\Phi}{dt} = -\frac{1}{l_c}\Psi + \frac{1}{2\pi l_c}\int_0^{2\pi} C_{ss}(\Phi + A\sin\theta)d\theta + g_2(A,\Phi,\Psi)u \tag{13}$$

$$\frac{d\Psi}{dt} = \frac{1}{4B^2 l_c}[\Phi - F(\gamma,\Psi)] + g_3(A,\Phi,\Psi)u \tag{14}$$

This Hopf bifurcation corresponds to a pitchfork bifurcation from the nominal equilibrium point $x^0(\gamma)$ in the original system.

4) Besides the monitoring/control schemes discussed above, we also contributed to other aspects of the active stall control problem for axial flow compression systems. In the thesis [8] and the papers [9],[10], deficiencies present in previous bifurcation control designs were analyzed and addressed by modifying the stall controllers. The first of these deficiencies is the appearance of controller-induced limit cycles as the throttle is closed beyond the bifurcation value. These limit cycles were found numerically by previous researchers, but no analysis of their existence and detailed behavior had previously been given. Our work has filled this gap, and also addressed controller design issues from a basic perspective. The second deficiency, which had not previously been discussed in the literature, is the fact that the achieved pressure rise in the controlled system tends to decrease steadily beyond the bifurcation point. This was probably not mentioned by researchers as a problem because post-stall stabilization was the main goal. However, it would clearly be beneficial of a high pressure rise could be maintained for significant deviations of the system into the post-stall regime. Our work in the publications [8]-[10] has resulted in modifications to the bifurcation control designs announced previously that indeed achieve this type of enhanced operability even past the stall point.

5) We continued our investigations into participation factors as a tool for actuator and sensor placement in stall monitoring and control of axial flow compressors. Our major achievement in this area is a gneralization of the participation factors notion to a new concept of input/output participation factors. These provide a clear methodology for determining optimal locations for placement of sensors and actuators for enhancing the instability warning

signal as much as possible. We also linked participation factors to advanced signal processing algorithms for computation of dominant modes from an output data record. Our publications on these topics thus far under this grant are [11],[12],[31].

6) Various attempts, analytical and numerical, were made throughout the course of the research project to obtain tools for detection of the direction of bifurcation in addition to the presence of an impending bifurcation. Among the analytical approaches employed was the use of higher order spectra. Most of these attempts proved fruitless. However, since the end of the research project, the Principal Investigator and his students have made significant progress on this important issue. A proposal has been submitted to support detailed pursuit of the ideas and application to several important problems were high performance requirements often raise the risk for stability loss.

7) Finally, the research project addressed cross-disciplinary issues and there was a beneficial interaction with ongoing work under a MURI on Active Control of Dynamical Systems [15]-[25],[30].

3 Personnel Supported

The following individuals have received support and/or been associated with this this grant: Dr. Eyad H. Abed (Professor and PI), Mr. Taihyun Kim (Ph.D. Candidate, Later Postdoctoral Fellow), Mr. Munther Hassouneh (M.S. and now Ph.D. student), Ms. Julide Tiglay (M.S. Student), Mr. Hassan Yaghoobi (Ph.D. Candidate), Mr. Chung-chieh Fang (Ph.D. Candidate), Mr. Mahir Nayfeh (Ph.D. Candidate).

4 Publications

[1] T. Kim and E.H. Abed, "Closed-loop monitoring systems for detecting incipient instability," *IEEE Trans. Circuits and Systems, I: Fundamental Theory and Applications*, in press.

[2] T. Kim and E.H. Abed, "Closed-loop stability monitoring of axial flow compression systems," *Nonlinear Dynamics*, Vol. 20, No. 2, pp. 181-196, October 1999.

[3] Taihyun Kim, *Noisy Precursors for Nonlinear System Instability with Application to Axial Flow Compressors*, Ph.D. Dissertation, Dept. of Electrical Engineering, and the Inst. for Systems Research, ISR Tech Rept No. Ph.D. 97-5, 1997, University of Maryland, 1997.

[4] T. Kim and E.H. Abed, "Stationary bifurcation control of systems with uncontrollable linearization," *International Journal of Control*, in press.

[5] T. Kim and E.H. Abed, "Precursor-based stability monitoring of axial flow compression systems," *Proc. American Control Conference*, June 2-4, 1999, San Diego, pp. 2657-2662.

[6] T. Kim and E.H. Abed, "Closed-loop monitoring systems for detecting incipient instability," *Proc. 37th IEEE Conference on Decision and Control*, Tampa, Dec. 16-18, 1998 (invited), pp. 3033-3039.

[7] E.H. Abed and M.A. Hassouneh, "Bifurcation control and stability monitoring," *Modern Applied Mathematics Techniques in Circuits, Systems and Control*, N.E. Matsórakis, Editor, pp. 284-288, Athens: World Scientific and Engineering Press, 1999.

[8] M.A. Nayfeh, *Active Control of Stall and Surge in Aeroengine Compression Systems*, Ph.D. Dissertation, Dept. of Electrical Engineering, University of Maryland, August 1998.

[9] M.A. Nayfeh and E.H. Abed, "High-gain feedback control of rotating stall in axial flow compressors," submitted to *Automatica*.

[10] M.A. Nayfeh and E.H. Abed, "High-gain feedback control of surge and rotating stall in axial flow compressors," *Proc. American Control Conference*, June 2-4, 1999, San Diego, pp. 2663-2667.

[11] H. Yaghoobi and E.H. Abed, "Optimal actuator and sensor placement for modal and stability monitoring," *Proc. American Control Conference*, June 2-4, 1999, San Diego, pp. 3702-3707.

[12] E.H. Abed, D. Lindsay and W.A. Hashlamoun, "On participation factors for linear systems," *Automatica*, Vol. 36, No. 10, October 2000, in press.

[13] E.H. Abed, "Bifurcation control of compressors," *Nontraditional Control Workshop*, Virginia Tech, Blacksburg, VA, Apr. 15, 1998.

[14] E.H. Abed, "Control of bifurcations," in *EOLSS: Encyclopedia of Life Support Systems*, Sec. 6.43: Control Systems, Robotics and Automation, (A UNESCO Project), to appear,

2001.

[15] C.-C. Fang and E.H. Abed, "Discrete-time integral control of PWM DC-DC converters," submitted to the *IEEE Trans. Power Electronics.*

[16] C.-C. Fang and E.H. Abed, "Limit cycle stabilization in PWM DC-DC converters," *Proc. 37th IEEE Conference on Decision and Control*, Tampa, Dec. 16-18, 1998 (invited), pp. 3046-3051.

[17] C.-C. Fang and E.H. Abed, "Saddle-node bifurcation and Neimark bifurcation in PWM DC-DC converters," in *Nonlinear Phenomena in Power Electronics: Attractors, Bifurcations, Chaos and Nonlinear Control*, S. Banerjee and G.C. Verghese, Editors, New York: IEEE Press, to appear.

[18] C.-C. Fang and E.H. Abed, "Sampled-data modeling and analysis of closed-loop PWM DC-DC converters," submitted to the *IEEE Trans. Power Electronics.*

[19] C.-C. Fang and E.H. Abed, "Sampled-data modeling and analysis of the power stage of PWM DC-DC converters," *International Journal of Electronics*, in press.

[20] C.-C. Fang and E.H. Abed, "Robust Stabilization of Limit Cycles in PWM DC-DC Converters," *Nonlinear Dynamics*, in press.

[21] C.-C. Fang and E.H. Abed, "Analysis and control of period doubling bifurcation in buck converters using harmonic balance," *Latin American Applied Research: An International Journal*, Special issue on Bifurcation Control: Methodologies and Applications, to appear, July 2001.

[22] C.-C. Fang and E.H. Abed, "Output regulation of DC-DC switching converters using discrete-time integral control," *Proc. American Control Conference*, June 2-4, 1999, San Diego, pp. 1052-1056.

[23] C.-C. Fang and E.H. Abed, "Sampled-data modeling and analysis of closed-loop PWM DC-DC converters," *Proc. Internat. Symp. Circuits and Systems*, Orlando, FL, May 30-June 2, 1999, pp. 110-115.

[24] P. Ranjan and E.H. Abed, "Enhancing detectability of bifurcations in DC-DC converters by stochastic resonance," *Proc. 39th IEEE Conference on Decision and Control*, Sidney, Australia, Dec. 2000 (invited), to appear.

[25] E.H. Abed, "Control of nonlinear phenomena in power electronic circuits," Session VIII, System Stability and Power Quality Issues, *1998 ONR-Drexel-NSWC WORKSHOP on Electric Shipboard System Modeling, Simulation and Control*, June 22-23, 1998, Philadelphia (invited panelist).

[26] T. Kim and E.H. Abed, "Stationary bifurcation control with uncontrollable linearization," presented at *A Symposium to Honor Professor Ali Nayfeh, ASME Mechanics and Materials Conference*, Blacksburg, VA, June 27-30, 1999.

[27] M.A. Nayfeh and E.H. Abed, "High-gain feedback control of axial flow compressor stall phenomena," presented at *A Symposium to Honor Professor Ali Nayfeh, ASME Mechanics and Materials Conference*, Blacksburg, VA, June 27-30, 1999.

[28] E.H. Abed and M.A. Hassouneh, "Bifurcation control and stability monitoring," presented at *The 3rd IMACS/IEEE Internat. Multiconference on Circuits, Systems, Communications and Computers*, Athens, July 4-8, 1999.

[29] E.H. Abed, "Monitoring the stability of two time-scale nonlinear uncertain systems," to be presented at the *Workshop on Singular Perturbations in Control in Memory of A.A. Pervozvansky*, Adelaide, Australia, December 7-10, 2000.

[30] Chung-Chieh Fang, *Sampled-Data Analysis and Control of DC-DC Switching Converters*, Dept. of Electrical Engineering, and Inst. for Systems Research, ISR Tech Rept No. Ph.D. 97-5, 1997.

[31] Hassan Yaghoobi, *Control and Monitoring of Nonlinear Instabilities*, Ph.D. thesis in preparation, Dept. of Electrical Engineering, and the Inst. for Systems Research, University of Maryland, Expected completion: August 2000.

5 Interactions/Transitions

1) Our work under AFOSR sponsorship on bifurcation control and applications to compression systems has motivated a significant amount of research by others. Much of this research addresses compressor stall control issues. However, transition has also occurred in other areas, such as control of laser instabilities and flight control.

2) Dr. Abed co-organized a the Control of Bifurcations and Chaos Workshop, at the 1998 IEEE Conference on Decision and Control in Tampa, Dec. 1998. He also delivered a presentation entitled Bifurcation Theory and Bifurcation Control at the workshop. The workshop was well-attended.

3) A two-part presentation was given by E.H. Abed at the United Technologies Research Center, East Hartford, CT on July 2, 1998. The first part focused on the analysis and control of period doubling bifurcation. The second part was an overview of the project results on axial flow compressor stall monitoring and control.

4) Contacts were made with Dr. Kevin Wise of Boeing to learn about aircraft applications of real-time modal monitoring. The papers and insights he provided were invaluable in our work.

5) A summary lecture on "Bifurcation control of compressors," was given at the ONR *Non-traditional Control Workshop* at Virginia Tech, on April 15, 1998. The Workshop brought together researchers in control and applications to help in formulating directions in ONR's funding for control research.

6) The work under this project contributes to a chapter [14] written by Dr. Abed that will appear in a major UNESCO-funded publication, the Encyclopedia of Life Support Systems.

7) Dr. Abed is Guest Editor of a special issue of the *Journal of Vibration and Control* on the subject of bifurcation control and applications.

8) Dr. Abed was an invited panelist at the *ONR-Drexel-NSWC WORKSHOP on Electric Shipboard System Modeling, Simulation and Control*, June 22-23, 1998, in Philadelphia. He addressed nonlinear control issues that are common to jet engine compressors and power electronics.

6 Honors/Awards

During the term of the grant, the Principal Investigator (Eyad H. Abed) was the recipient of the Senior Fulbright Scholar Award.