FINAL REPORT
UNITED STATES DEPARTMENT OF ENERGY GRANT

PROJECT TITLE:	**"Nonlinear Dynamic Systems Response to Non-Stationary Excitation Using the Wavelet Transform"**
PRINCIPAL INVESTIGATES:	**Spanos, Pol D.** **LB Ryon Chair in Engineering**
RECIPIENT ORGANIZATION:	**Rice University** **PO Box 1892** **Houston, Texas 77251-1892**
AWARD NUMBER:	**DE-FG03-95 ER 14500**
UNEXPENDED FUNDS:	**- 0 -**
PROJECT OFFICER:	**Fitzsimmons, Timothy, Ph.D.**
REPORTING PERIOD:	**1 January 2003 thru 15 January 2006**

I. PRINCIPAL PROJECT PERSONNEL: SPANOS, POL D.

A. ROLE IN THE PROJECT

He initiated and coordinated the: collection of pertinent data, the pursuing of various solution techniques, and the synthesis/processing of various manuscripts disseminating the findings of the research. He provided mentorship to the four (4) Ph.D. students, and three (3) post-doctoral fellows who participated in the process.

B. PRINCIPAL AREAS OF RESEARCH AND EXPERTISE

Dynamics and vibrations of dynamical systems with emphasis on stochastic, nonlinear, and signal processing aspects.

C. PERCENTAGE OF TIME DEVOTED TO THE PROJECT

The equivalent of four (4) months per year (no compensation from DOE was provided for the entire period of four (4) months per year).

D. EDUCATION

Five (5) year diploma in Mechanical Engineering and Engineering Science, National Technical University, 1973; M.S. in Civil Engineering, California Institute of Technology, 1974; Ph.D. in Applied Mechanics with first minor in Applied Mathematics, and second minor in Business Economics, California Institute of Technology, 1976.

E. EMPLOYMENT HISTORY

Research Fellow, California Institute of Technology, 1976-1977
Assistant Professor, University of Texas at Austin, 1977-1981
Associate Professor (tenured), University of Texas at Austin, 1981-1983
P.D. Henderson Associate Professor, University of Texas at Austin, 1983-1984
Professor of Mechanical and Civil Engineering, Rice University, 1984-1988
L.B. Ryon Endowed Chair in Engineering, Rice University, 1988 to Present

F. PROFESSIONAL ACTIVITIES AND HONORS

Panhellenic Laud in mathematics from the Greek Mathematical Society (1968). European Award of Science (College Division), N.V. Phillipps Company, Eindhoven, Netherlands (1969). Several prestigious awards from the State of Texas; the 1982 Pi Tau Sigma gold medal for outstanding achievement (within 10 years from graduation) from the American Society of Mechanical Engineers; a 1984 Presidential Young Investigator Award from the National Science Foundation; a certificate of merit for new technology from McDonnell Douglas Astronautics Company; a 1989 Huber Research Prize for outstanding research in engineering mechanics from the American Society of Civil Engineers; the 1991 Larson Award for outstanding achievement (within 20 years from graduation) from the American Society of Mechanical Engineers; the 1992 Freudenthal Medal from the American Society of Civil Engineers for lifetime contributions to Probabilistic Methods in Civil and Mechanical Engineering; a 1995 Senior Researcher Prize from the Humboldt Foundation, Germany; the 1997 Stochastic Dynamics Research Prize, International Association for Structural Safety and Reliability; the 1999 Newmark Medal from the American Society of Civil Engineers for lifetime contributions to structural dynamics.

Editor-in-Chief, International Journal of Non-Linear Mechanics. Managing Editor, Journal of Probabilistic Engineering Mechanics. Fellow, ASCE, ASME, and the American Academy of Mechanics. Member, Earthquake Engineering Research Institute and of the National Academy of Engineering (USA). Corresponding member, Academy of Athens (National Academy of Greece). Since 1988, holds the LB Ryon Endowed Chair in Engineering at Rice University in Houston, Texas.

Given invited lectures and short courses as a visiting professor in North, Central and South America; Western and Eastern Europe; India; Japan; and the USSR (former). Has extensive worldwide consulting experience for organizations such as D'Appolonia, Italy; Conoco, Houston, Texas; McDonnell Douglas Astronautics, Houston, Texas; Lockheed, Inc., Huntsville, Alabama; Exxon, Houston, Texas; Jet Propulsion Laboratory; and Aerospatiale, France.

G. RELEVANT PUBLICATIONS NOT EMANATING FROM THIS PROJECT

More than 300 papers in archival journals and technical conferences, and 19 books on dynamics of rigid and flexible bodies with an emphasis on nonlinear and probabilistic aspects, and applications to aerospace engineering, structural engineering, offshore engineering, vehicle engineering and materials engineering.

II. ADDITIONAL PROJECT PERSONNEL

Under the support of the grant, four (4) students have been granted their Ph.D. degree, and three (3) post-doctoral fellows have participated in conducting relevant research, and preparing the publications disseminating the research.

III. PROJECT OVERVIEW

A. PROJECT OBJECTIVES ACCOMPLISHED

The objective of this research project has been the development of techniques for estimating the power spectra of stochastic processes using wavelet transform, and the development of related techniques for determining the response of linear/nonlinear systems to excitations which are described via the wavelet transform. Both of the objectives have been achieved, and the research findings have been disseminated in papers in archival journals and technical conferences.

1. Project Overview

A wavelet based method was developed to estimate the evolutionary power spectral density (EPSD) of non-stationary stochastic processes. The method relied on the property that the continuous wavelet transform of a non-stationary process could be treated as a stochastic process with EPSD given in terms of the EPSD of the process in a closed form. This yielded an equation in the frequency domain relating the instantaneous mean-square value of the wavelet transform to the EPSD of the process. A number of these equations were considered, each related to a certain scale of the wavelet transform, in conjunction with representing the target EPSD as a sum of time-independent shape functions modulated by time-dependent coefficients; the squared module of the Fourier transforms of the wavelets associated with the selected scales are taken as shape functions. This lead to a linear system of equations which were solved to determine the unknown time-dependent coefficients; the same system matrix applied for all time instances. Numerical examples demonstrated the accuracy and computational efficiency of the proposed method.

The wavelet transform was applied to the problem of determining the response of a MDOF linear system to non-stationary stochastic excitation. A time-frequency representation of the frequency response matrix was developed involving the harmonic wavelet scheme. Further, excitation-response relationships in the harmonic representation scheme were derived. Specifically, it was shown that the wavelet coefficients of the response could be determined by convolving the wavelet coefficients of the excitation with the wavelet representation of the system at each scale. Numerical results pertaining to the response of a MDOF linear system subject to filtered white noise excitation have shown that the proposed method captures quite reliably the variation of the frequency temporal content of the system response.

The problem of estimating the power spectrum of non-stationary stochastic process via the wavelet transform was addressed. For this purpose the family of the harmonic wavelets was chosen due to the non-overlapping, in the frequency domain, feature of wavelets belonging to the adjacent scales. Dyadic, generalized, and filtered harmonic wavelets were used. Explicit expressions were derived relating the moments of the coefficients of the wavelets based representation of the process and of its evolving in time spectral content. In this regard, the filtered harmonic wavelet scheme was found to be the most effective one. Mathematical expressions were derived elucidating the observations and the analogy between the wavelets-based and the traditional (involving trigonometric functions) representations of the spectral content of stochastic processes. The derivation of these expressions, were included as an appendix to the main body of the paper. The theoretical results have been used first to study the spectrum of a separable non-stationary process represented by the product of a stationary process with a “slowly” varying deterministic modulating envelope. In this regard, it was found that the degree of slow variation is subject to quantification, and the classical formula for the spectral estimation involving the product of the spectrum of the stationary process with the square of the modulating envelope did not necessarily yield results identical to those derived by a wavelets-based analysis. Thus, caution should be exercised in using this formula in refined local features capturing signal processing procedures.

A wavelet based equivalent linearization method was developed for determining the evolutionary power spectrum of the response of a Duffing oscillator excited by non-stationary processes. Harmonic wavelets were used to decompose the excitation into components with non-overlapping frequency bands. For each frequency band, a numerical linearization procedure was applied to calculate equivalent stiffness values and the response for that particular scale was found. Finally, a bank of accelerograms was used to demonstrate the applicability of the proposed method in estimating the power spectral density of the response of a single degree-of-freedom system with cubic nonlinearity. It was shown that the developed numerical approach gave a reliable estimate of the power spectral density of the response of the Duffing oscillator. Clearly, this is a very powerful technique, which is applicable for a broad class of problems of nonlinear, stochastic dynamics, involving wavelet-based definition of the excitation.

2. Project Output

The project has had both a research component and a pedagogical component. In this regard, several technical reports (see list of references), four Ph.D. degrees have been granted, and three post-doctoral fellows have been supported to participate in the program.

IV. REFERENCES

1. Spanos, P. and Failla, G., “Evolutionary Spectra Estimation Using Wavelets,”Journal of Engineering Mechanics, American Society of Civil Engineers.

2. Tratskas, P. and Spanos, P., “Linear Multi-Degree-of-Freedom System Stochastic Response by using the Harmonic Wavelet Transform,” Journal of Applied Mechanics.

3. Spanos, P., “Numerical wavelets and applications in stochastic dynamics (in Greek). Proceedings of the Academy of Athens (National Academy of Greece), Vol. 79, pp. 2009-249, 2004.

4. Spanos, P. and Tezcan J., “Spectrum estimation of non-stationary stochastic processes using harmonic wavelets, 7th National Congress on Mechanics, Chania, Greece (06/24-06/26), pp. 1-12, 2004.

5. Spanos, P., Failla G. and N. Politis, “Wavelet concepts and applications,” Chapter in *Encyclopedia of Vibrations, CRC Press, Boca Raton, Florida, pp. 1-45, 2005.*

6. Spanos, P. and Failla, G., “Wavelets: Theoretical Concepts and Vibrations Applications,” Shock and Vibration Digest, Vol. 37, No. 5, pp. 359-375, 2005.

7. Spanos, P. Tezcan, J. and Tratskas, P., “Stochastic Processes Evolutionary Spectrum Estimation via the Wavelet Spectrum,” Journal of Computational Methods in Applied Mechanics and Engineering, Vol. 194, pp. 1367-1383, 2005.

8. Spanos, P.D. and Tezcan, J., “A numerical approach for nonlinear system response determination via wavelets,” Proceedings Fifth International Conference on Computational Stochastic Mechanics, Rodos, June 21-23, 2006.

9. Spanos, P., Failla G., Santini A. and Pappatico M., “Damage Detection in Euler-Bernoulli Beams via Spatial Wavelets Analysis,” Journal of Structural Control and Health Monitoring, Vol. 13, pp. 472-487, 2006.

10. Politis, N., “Joint Time Frequency Analysis in Structural Engineering Applications,” 2/2005, Doctoral Thesis.

11. Teczan, J., “Non-Linear System Response to Non-Stationary Input Processes Using Harmonic Wavelets,” 04/2005, Doctoral Thesis.