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13. ABSTRACT (Maximum 200 words) This Final Report summarizes the results obtained with a synergistic measurement system used as the basis of a diagnostic system for monitoring and characterizing aircraft materials and structures. The system utilizes the development of an empirical model describing the characteristics and dynamics of the material or structure. It is demonstrated that this approach is useful for processing the signals of linear as well as non-linear systems. The linear modeler has been used to obtain a characterization of the strength and location of impacts on a truss-like structure. While the more general, automatic modeler which resembles a multi-dimensional, non-parametric regression approach was utilized to locate sources of acoustic emissions in a structure and also to predict fatigue crack growth in Al-alloys under different loading conditions. Applications have been to measured as well as existing data which comprise a corrosion-fatigue material property data base. It was found that the prediction performance of the modeler is excellent if the measured input data closely resembles one of the previous data sets residing in the memory. An enhanced predictive performance can be obtained from the modeler if a predictor-corrector algorithm is used. DTIC QUALITY INSPECTED 2					
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Final Report

Synergistic Diagnostics
of Aircraft Materials and Structures

AFOSR Contract #F49620-95-1-0383

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Report for the period:

May 15, 1995 - August 14, 1997

March 15, 1998

1 General Objectives of this Project

The focus of this research program has been the development of new and innovative integrated approaches for monitoring the integrity of aging aircraft materials and structural components. We call this approach *synergistic diagnostics* because it is based on the union of *sensing, processing, modeling* and *forecasting* of the condition of a structure with respect to its performance. *Synergistic diagnostics* touches on the fields of measurement science, signal processing, materials failure, chaotic dynamics, adaptive systems and neural networks.

2 Specific Objectives of this Project

The specific tasks that were to be carried out under this project include the following:

1. We proposed to establish the feasibility of the *synergistic diagnostics* approach by demonstrating the operation of an intelligent structural monitoring system on a simple structure, using just one sensed variable. Measured material damage data was to be collected in our laboratory and this was to be used for training and testing the synergistic measurement system. The focus was to be on the development of damage source location and damage identification procedures which can be reliably implemented on a complex structure. We wished to evaluate these procedures as a function of corrosion and damage evolution. Experiments and simulations were to be carried out. And such data were to be used to establish the operating conditions of the structural monitoring system.
2. We sought to develop and demonstrate a multi-sensor, intelligent structural monitoring system which relies on signals sensitive to material or structural damage as well as one or more environmental variables. Training and demonstration of the system was to be with data obtained from our own experiments as well as from other sources, as we could obtain. The principal goal was to demonstrate the predictive capabilities of the system.
3. We sought to develop a passive, acoustic-based (AE) monitoring system for the characterization of damage including crack growth and corrosion as found in aircraft structural materials and components.

In our original proposal written in March 1995, we also proposed to explore in the third year of the project the possibility of developing an acoustic-based, acoustic emission monitoring system for the detection and characterization of corroded aircraft structural materials

and assemblies. We sought to predict its development and to develop means for applying control signals that either mitigate the corrosion or provide a means for safely operating a corroding structural component. However this task in the original proposal was not funded.

3 Accomplishments: May 15, 1995–August 14, 1997

During the above-mentioned time period of this research project, we have achieved progress in each of the areas listed in the previous section. The most significant achievement was the publication of our monograph on *synergistic measurement systems* in February 1997 by Springer-Verlag.[1] This project enabled the PI to complete the preparation of this monograph and this support is gratefully acknowledged.

1. I. Grabec and W. Sachse, *Synergetics of Measurement, Prediction and Control*, Springer-Verlag, Heidelberg (1997).

We also participated in two Reviews organized directly or indirectly by the AFOSR. We presented an overview of this program and reviewed the accomplishments made during the first year of this project at an AFOSR Contractors' Meeting of the Structural Mechanics Program that was held in Virginia Beach, VA, June 1996.[2]

2. W. Sachse, "Synergistic diagnostics of aircraft materials and structures", in *Proceedings from the Air Force Office of Scientific Research Structural Mechanics Program Contractors Meeting*, June 25–27, 1996, AFOSR Report, Washington, D. C. (1996), pp. 33–34; pp. 241–255.

The progress achieved during the second year of this project was reported at the *Workshop on Intelligent NDE Sciences for Aging and Futuristic Aircraft* which was held at the FAST Center for Structural Integrity of Aerospace Systems at the University of Texas at El Paso in September, October 1997.[3]

3. X. Lu, E. Govekar, W. Sachse and I. Grabec, "Synergistic diagnostics of aircraft materials and structures", in *Proceedings of Intelligent NDE Sciences for Aging and Futuristic Aircraft*, C. Ferregut, R. Osegueda and A. Nuñez, eds., Texas Western Press, El Paso, TX (1998), pp. 11–22.

During the early period of this project we applied the so-called *linear modeler*[1] as the basis of a multi-channel acoustic source location processor. Using this, we successfully

demonstrated locating sources of acoustic emissions in complex-shaped structural elements (i.e. truss-like sections). Over the entire period of this contract, we adapted the *automatic modeler* concept[1] to learn from and subsequently predict the location of acoustic sources and the fatigue fracture of a number of aircraft Al-alloys. This approach is reviewed in the following sub-section and the accomplishments made will be summarized in the subsequent sub-sections.

3.1 Synergistic Measurement System and Automatic Modeler

Central to the synergistic measurement system we have investigated under this project is a neural-like, adaptive signal processing procedure which permits modeling the non-linear relationships between measured signals or information and the condition and specifically in this project, the fatigue properties of a specimen. The procedure we have employed relies on a statistical treatment of measured data to generate an empirical modeler of the natural law describing the phenomena. Such an *automatic modeler*[1] is based on a self-organized, optimal preservation of empirical information that utilizes the principle of maximum entropy of information and an optimal, associative estimation of missing information resembling a non-parametric regression. The approach corresponds, in part, to a neural network based on a set of radial basis functions or a 3-layer perceptron.[1]

For example, in applying this approach to the fracture and lifetime prediction of fatigue-loaded specimens, we denote the initial s -components of the measured crack growth rate data as $S = (x_1, x_2, \dots, x_s)$. These may be functions of crack length a or other controlling parameters, such as stress intensity factors or energy release rate. The subsequent crack growth rate data da/dn are written as $P = (x_{s+1}, x_{s+2}, \dots, x_{s+P})$. Thus, the concatenated signal description of the crack growth rate of a specimen undergoing fatigue is expressed by the data vector

$$X = S \oplus P = (x_1, x_2, \dots, x_s, x_{s+1}, \dots, x_{s+P}) \quad (1)$$

For the case of acoustic emission source location studies, the components comprising the vector S may be the detected AE waveform signals while the vector P will refer to the coordinates of the source point or other parameters characterizing the source or even the structure.

To learn from examples, one collects the data vectors $X_1, X_2, \dots, X_N$ during a series of training measurements. These data vectors form the basis of the *memory* of the modeler. The formation of this memory corresponds to an *adaptation* of the system. For processes in which there is a continuous set of measured data, as, for example, continuous acous-

tic emission or electrical impedance data from the growing crack, one represents the data by a fixed, finite set of representative *prototype data* vectors which are selected by a self-organization procedure.[1] Once the memory has been developed, an optimal estimation of the material property characteristics $\hat{P}_O(S)$ from the measured sensor data is obtained via *multi-dimensional, non-parametric regression*. This is the *analysis* mode of the modeler. Specifically,

$$\hat{P}_O(S) = \int P \cdot f(P|S) dP \implies \sum_{n=1}^N C_n P_n \quad (2)$$

where the *measure of similarity* is expressed by the coefficients

$$C_n = \frac{g(S - S_n)}{\sum_{n=1}^N g(S - S_n)} \quad (3)$$

Here, g represents the Gaussian functions which are formed from the data measured during learning, S_n , and during an subsequent, actual experiment, S . In this project, we trained the automatic modeler to model the fatigue crack phenomenon so that it could be subsequently used to predict the crack growth and hence the lifetime of a specimen. As one of our most significant accomplishments under this project, we have demonstrated the utility of this approach for predicting crack growth in aircraft Al-alloys loaded under tension and torsion mixed-mode fatigue loading.

The general application of the modeler to process ultrasonic waveform data was presented during the period of this contract at an international conference and the proceedings of that talk are given in the following reference:[4]

4. I. Grabec and W. Sachse, "Empirical modeling of ultrasonic phenomena". *Ultrasonics*, **34**, 451-454 (1996).

3.2 Source Location in Complex Structures

The multiplicity of propagating paths and the effects of dispersion complicate the efforts in locating sources of emission in complex structural elements such as truss-like sections which are used as the skeleton for many airframe structural components. Because of these wave propagational effects, all attempts to analyze the signals detected by an array of sensors using simple triangulation or other direct source location procedures usually fail. And yet it is recognized that in a system being continuously monitored, if one can reliably locate an active source of emission, this would provide invaluable information to aircraft maintenance personnel and possibly even pilots about impending danger to the integrity of an airframe. It is for this reason that we focused our attention to the acoustic emission source location

problem rather than the source identification problem. The latter is far more complex and its solution will likely not provide the critical information that is needed to quickly and correctly assess the safety of an aircraft.

The approach we developed during the first year of this project has been summarized in the First-year Annual Report which was submitted to the AFOSR in August 1997 [5] and so these results will not be repeated here.

5. W. Sachse, "Synergistic diagnostics of aircraft materials and structures", Annual Report for AFOSR Contract #F49620-95-1-0383, August 1996.

In the second year of this project we developed an autonomous system for locating sources of acoustic emission in a thick, flat plate. [6] The system relies on a small array of sensors to detect the signals and a processing system based on the *automatic modeler* which was described in the previous sub-section. The use of a small array of sensors minimizes differences in the effects of wave dispersion and attenuation on the detected signals. In using this approach, no preprocessing of the input waveform data is required and no determination of wave arrival times need to be made. Novel also is that the development of the memory of the modeler is achieved using synthetic waveform data. After training, the modeler is used to recall the source location parameters by presenting to it, actual, complete AE signals detected by the small array. The operation of the system has been demonstrated with both synthetic as well as measured waveforms corresponding to impact and step-unloading forces on a thick plate in which the signals were detected with a 3-sensor array of conventional small-aperture piezoelectric transducers. A paper on this work was presented at *Ultrasonics International'97* which was held in Delft, Holland, July 1997.

6. X. Lu, W. Sachse and I. Grabec, "Use of an automatic modeler and a small receiver array for acoustic emission (AE) source location". In Press: *Ultrasonics*.

One of our principal goals of our research program was to consider the development of acoustic emission source location procedures utilizing specific AE waveform parameters to characterize the size and growth of a crack in a fatigue-loaded, thin-plate specimen of Al-alloy.[7] We found however, that such data often does not reliably correlate with the optically measured growth characteristics of the crack.[7] The experiments showed that AE data may not always be a suitably reliable indicator of crack growth and hence it is likely that one will have to rely on other crack length measurement techniques such as optical or other measurements as the source of the input data to the modeler.[7] These results are described in the following paper:

7. X. Lu, W. Sachse and I. Grabec, "Predictive measurement using AE: Fracture and lifetime of Al-alloys", MSC Report #8238, Materials Science Center, Cornell University, Ithaca, NY (August 1997). In press: *Nondestructive Characterization of Materials*, C. O. Ruud and R. E. Green, Eds., Plenum Press, New York (1998).

The unsuitability of AE measurements as a crack growth monitoring sensor led us to seek an alternate procedure for sizing cracks in plate-like specimens. Near the end of the second year of this project we developed a *self-calibrating*, active ultrasonic crack tip location procedure which is based on a wavespeed consistency condition being imposed on the measured arrival-times of signals detected by a three- or four-element, small-array of detectors.[8] There is the requirement that at least one of the detected signals must be a crack-tip diffracted signal. The wavespeed consistency condition leads to a determination of the crack tip location.

8. X. Lu and W. Sachse, "Self-calibrating active ultrasonic technique for crack tip location" MSC Report #8239, Materials Science Center, Cornell University, Ithaca, NY (August 1997).

Other than demonstrating the feasibility of this approach, time did not permit it to be implemented for actual crack length measurements during a fatigue test.

3.3 Fracture and Lifetime Prediction of Al-alloys

It is recognized that the pressurization of an aircraft fuselage results in both tensile and transverse (out-of-plane tearing) stresses on a crack near a lap joint.[9] Crack tip tensile stresses arise from the hoop stress in the fuselage skin while the out-of-plane tearing stresses arise from the internal pressure in the fuselage. It is for this reason that we carried out multi-mode fatigue tests to study the fatigue crack growth under both tensile and transverse shear stresses. Following up earlier work of Zehnder and Viz[9], we tested double-edge notched (DEN) specimens of 2024-T3 Al-alloys under constant amplitude cyclic tensile and torsional loadings using a conventional servo-hydraulic mechanical testing system. During the time period of this contract we completed fatigue studies of the above-mentioned alloys as well as 7076-T6 Al-alloy and Ti6Al4V. Fatigue measurements were also completed on single-edge notched specimens (SEN) of 2024-T3 and 7076-T6 Al-alloys.

4 Fatigue Modeling Based On Measured Crack Length

The research we have carried out under this project focused on the critical question whether a synergistic system can be adapted and subsequently used to predict fatigue crack growth.

To investigate this, we needed to collect precise crack growth data while a specimen was undergoing fatigue loading. As mentioned earlier, two kinds of specimens were fatigue tested. They included double-edge-notched (DEN) specimens, in which the crack growth from one of the notches was used to predict the growth of the crack emanating from the other notch and the others were single-edge notch specimens in which the crack growth prediction was based on the data collected from different specimens.

4.1 Crack Growth in Double-Edge-Notched Specimens

Fatigue crack growth measurements were carried out on double-edge-notched 2.29 mm-thick sheets of 2024-T3, 7076-T6 Al-alloys and Ti6Al4V. A description of the details of the experiments and the results that were obtained have been given in a previous report and so will not be repeated here.[5]. The results demonstrated that the crack growth could be predicted from a small number of initial crack length data points. But the results also showed that a reliable prediction of the crack length was only possible when the measured data, which is input to obtain the recall, reasonably closely corresponded to data already residing in the memory.

4.2 Crack Growth in Single-Edge-Notched Specimens

Since the cracks in DEN specimens may influence each other, we carried out a series of fatigue crack growth measurements on specimens with single-edge notches. As for the earlier tests, these were fabricated from 2.29 mm-thick sheets of 2024-T3 and 7076-T6 Al-alloys. As before, the crack growth data was collected on specimens undergoing tension-tension, torsion-torsion fatigue but over a broader range of maximum and minimum applied loads and torques than those used in the DEN tests. Details of the specimens and the testing parameters has been given in Ref. [3].

Optically measured crack growth rate data as a function of crack length obtained on the fracture specimens is depicted in Fig. 1. This data constitutes the *memory* of the modeler. Once this memory has been developed, it can be used to recover missing information in the data vectors (i. e. Eq. (2)) which are presented to it. Our aim was to recover the components of the missing property descriptors, P , which correspond to the expected crack growth rate. To illustrate the predictive capability of this approach, only the first ten, initial crack length data values a were input to the modeler from which the remaining evolution of the crack growth, da/dn , was predicted. That is, the modeler was operated as a *long-term predictor* in which a small number of crack growth data values were used to predict all of the expected, future values. We show in Figs. 2(a)-(b) the results of two blind experiments. These results

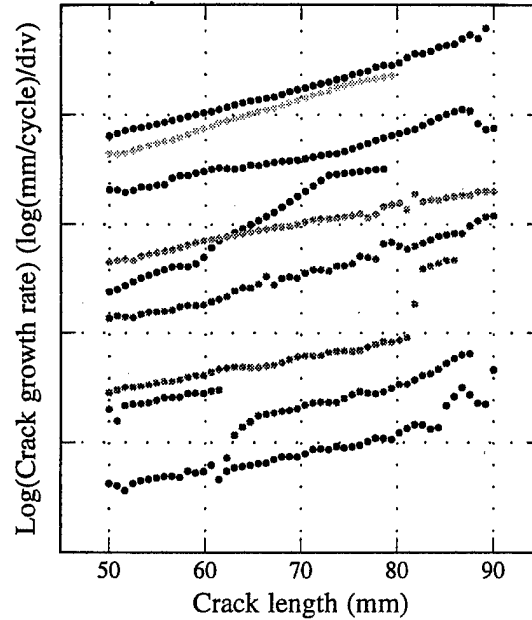


Figure 1: Crack growth data on 2024-T3 and 7075-T6 fatigued Al-alloy specimens which was used to develop the modeler *memory*. (The data are offset vertically for visibility.)

are taken from Ref. [3].

The results obtained under this contract show that reliable prediction of the crack growth appears to be only possible when the input data reasonably closely corresponds to data already residing in the memory. The result of the 7075-T6 Al-alloy specimen which is shown in Fig. 2(a) exhibits good agreement between the predicted and the subsequently measured crack growth curve. In this example, the first ten points of the measured data used for prediction as well as the subsequent, measured data closely resemble one of the curves in the memory which was generated under similar loading conditions but had a different initial crack length. In that case, the predictive capability of the automatic modeler, based on only the first few points in a crack-growth curve, seems to be quite good.

In contrast, the crack growth data for the 2024-T3 Al-alloy specimen differs significantly from each of the curves comprising the memory because the test shown in Fig. 2(b) was carried out under loading conditions which differed significantly from those used to generate the memory. It appears that under such loading conditions, the modeler cannot properly predict the crack growth. It may need to be trained with additional data such as loading information or other parameters which control the crack growth in order to improve its predictive capabilities. Exactly which data or parameters are the controlling factors in such crack growth and thus need to also be input to the modeler is not yet known and this remains a topic under study.

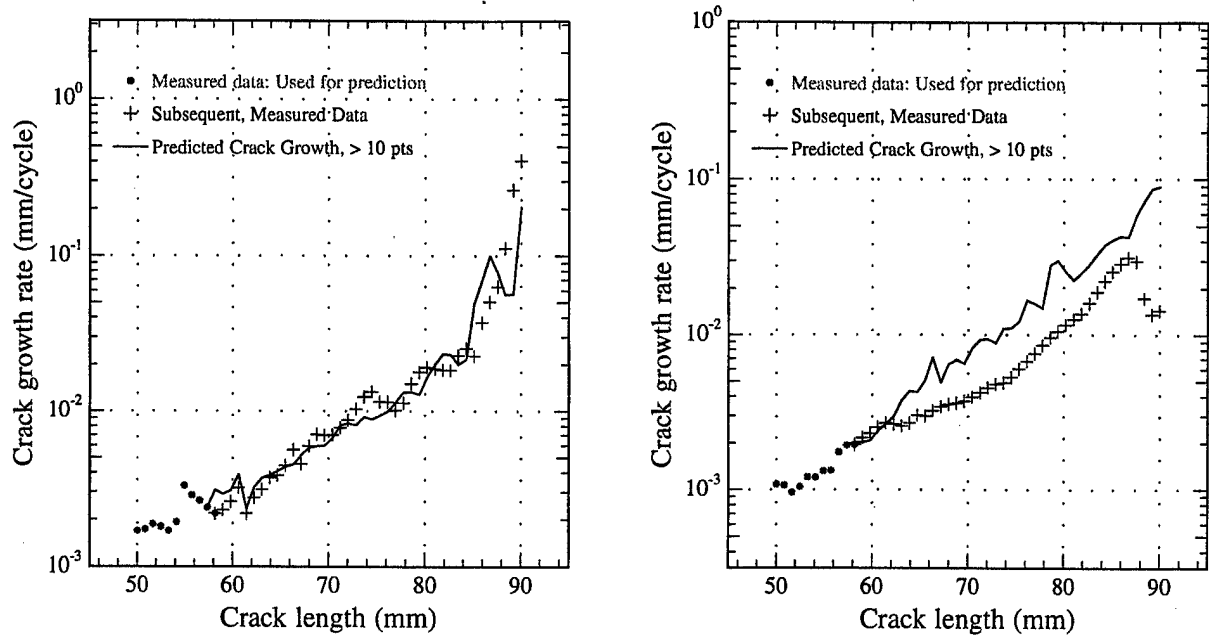


Figure 2: Modeler prediction of crack growth data in fatigue-loaded Al-alloy specimens. (a) 7075-T6 showing excellent prediction; (b) 2024-T3 showing poor prediction.

4.3 Predictor-Corrector Modelers

As mentioned above, the *long-term predictor* appears to be incapable of performing well when the first few data points do not resemble those in the memory. An alternative procedure that was developed during the second year of this project was a so-called *moving window predictor* in which a small number of data values are used to predict one or only a small number of expected future data values. Subsequent crack growth is predicted sequentially by moving the window of predicted crack growth rate data, step-by-step ahead. This procedure does nothing to improve the memory of the modeler.

For this reason we also developed a *predictor-corrector* algorithm which uses previously-measured crack growth data to predict the crack growth expected for only a small number of steps ahead. The predicted value is subsequently corrected by the actual, measured value and this, in turn, is used to dynamically update the memory. This leads quite naturally to the *one-step ahead predictor-corrector* in which the modeler uses the measured crack growth data $\{k-4, k-3, k-2, k-1 \text{ and } k\}$ to predict the crack growth just one step ahead, at $\{k+1\}$.

The performance of these different operating modes of the modeler is compared using the data previously shown in Fig.2(b). This is shown in Fig.3 in which the operating modes of the modeler are used with either five or ten initial points. The performance of each of the operating modes is shown. It is seen that nearly all of the enhanced prediction

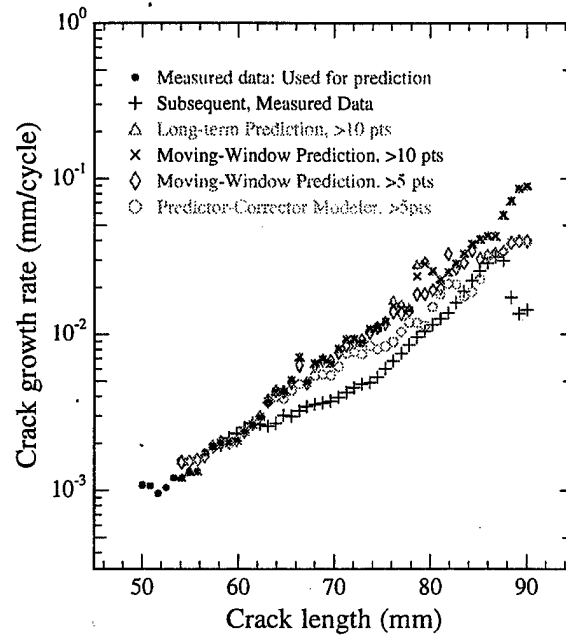


Figure 3: Performance enhancement of the modeler to predict fatigue crack growth in a 2024-T3 Al-alloy specimen which was not residing in the memory of the modeler. Tension-tension: 2-4 kips; torsion-torsion: 30-50 lbs-in. 12.42 Kcycles to failure.

approaches result in little improved performance of the modeler. But the prediction obtained by the predictor-corrector modeler with five initial points, approaches the actual, subsequent, measured data as the crack length increases.

4.4 Crack Prediction from a Material Property Data Base

To demonstrate the utility of the approach we have developed under this contract, we sought to obtain crack growth data which had been obtained by others on real aircraft Al-alloys. For the past several years a round-robin fatigue crack growth rate test program was carried out using "as received" as well as "artificially corroded" C/KC-135 fuselage and upper wing skin materials.[11] Four materials were investigated in the round-robin test program. Fatigue tests were carried out in tension-tension at two levels of humidity and two loading frequencies. The goal was to generate a data base which would subsequently provide a basis for calculating the crack growth parameters of corroded and non-corroded typical airframe materials.

In the final months of this project we obtained access to this fatigue crack growth data base and have used the data of four tests to develop the memory of the modeler. The results are depicted in Fig.4(a). Here K_{max} denotes the maximum stress intensity factor, R is the *min/max* fatigue load ratio and q is an empirical constant (equal to about 0.6). The first five crack growth data points collected in another test (same material, identical testing parameters) was then input to the modeler to forecast the subsequent predicted crack growth

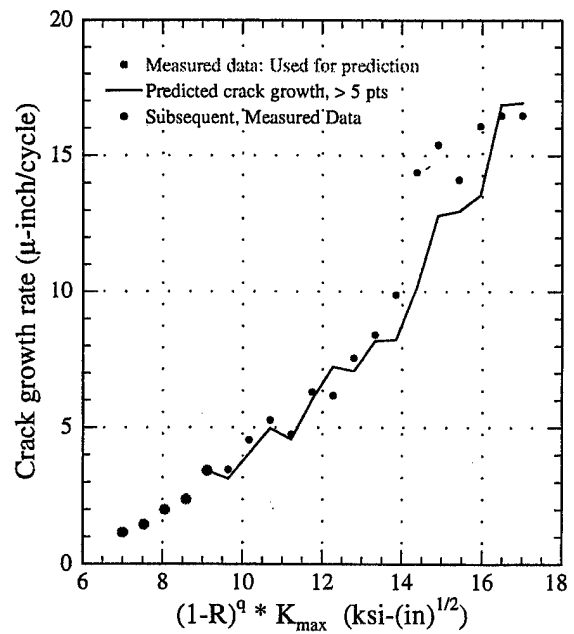
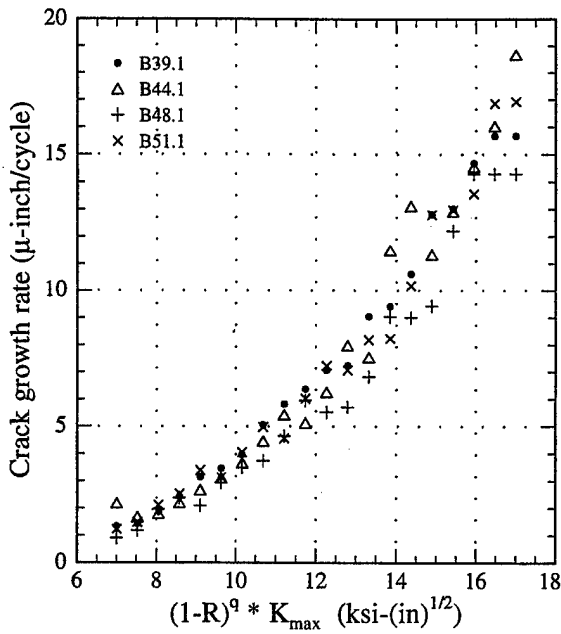


Figure 4: 2024-T3 Fatigue data base: As-received; tested at 15% relative humidity; 10 Hz testing frequency. (a) Development of the modeler memory; (b) Prediction of crack growth on a specimen not included in the memory.

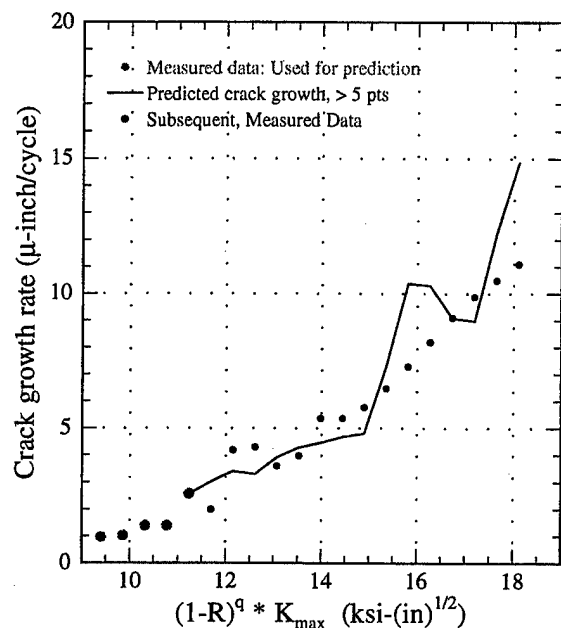
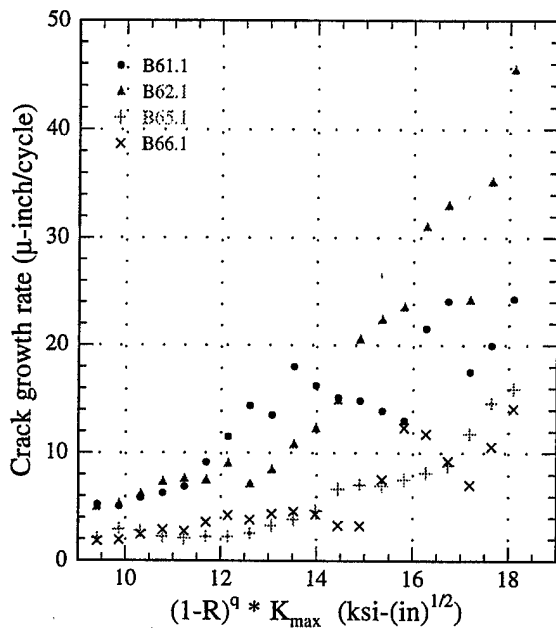


Figure 5: 2024-T3 Fatigue data base: As-received; tested at >85% relative humidity; 10 Hz testing frequency. (a) Development of the modeler memory; (b) Prediction of crack growth on a specimen not included in the memory.

curve. The result is shown in Fig. 4(b). The subsequent, actual measured crack growth data is also shown in the figure. The agreement between the prediction and that actually measured is excellent. The crack growth rate was correctly predicted.

In another repeat test, the fatigue crack growth data of specimens loaded in a corrosive environment, greater than 85% relative humidity was used. These results are shown in Figs. 5(a) and (b). While the data comprising the memory of the modeler shows considerably more variation, it is still able to adequately predict the crack growth rate for another test sample.

5 Summary Remarks

The results we have obtained during the 27 months of this contract effectively address the topics we proposed for study. We have demonstrated that the elements of a *synergistic measurement system* can serve as the basis of a diagnostic system for monitoring and characterizing aircraft materials and structures. The basis of the diagnostic system is the empirical development of a model describing the characteristics and dynamics of the material or structure. The model is hidden in the prototype data which constitute a memory. We have shown that this approach is useful for processing the signals of *linear* as well as *non-linear* systems. The *linear modeler* has been used to obtain a characterization of the strength and location of impacts on a truss-like structure.

The more general, *automatic modeler* which is really a *multi-dimensional, non-parametric regression* approach was been utilized to locate sources of acoustic emissions in a structure and also to predict fatigue crack growth in Al-alloys under different loading conditions. Applications have been to measured as well as existing data which comprise a corrosion-fatigue material property data base. It was found that the prediction performance of the modeler is excellent if the measured input data closely resembles one of the previous data sets residing in the *memory*. An enhanced predictive performance can be obtained from the modeler if a *predictor-corrector* algorithm is used which was also developed under this contract.

Our results have been presented in eight talks, five of which were presented at international conferences. Our results have also been published or accepted for publication in eight manuscripts or papers. A major monograph was also completed and published during the period of this contract.

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- [1] I. Grabec and W. Sachse, *Synergetics of Measurement, Prediction and Control*, Springer-Verlag, Heidelberg (1997).
- [2] *Proceedings from the Air Force Office of Scientific Research Structural Mechanics Program Contractors Meeting*, June 25–27, 1996, AFOSR Report, Washington, D. C. (1996), pp. 241–255.
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STP 1256, W. G. Reuter, J. H. Underwood and J. C. Newman, Jr., eds., American Society for Testing and Materials, Philadelphia (1995), pp. 631-651.

- [11] J. Luzar, *Integrated C/KC-135 Corrosion Program Round Robin Testing*, Report for AF Contract F34601-90-C-1336, Boeing Product Support Division, Wichita, KS (May 1996).

6 Presentations and Lectures given during the Contract Period

During the period of this contract the Principal Investigator or the research collaborators gave the following presentations and lectures:

1. "Empirical Modeling of Ultrasonic Phenomena", *Ultrasonics International'95*, Edinburgh, Scotland (July 7, 1995).
2. "Synergistic Measurement and Control Systems", Invited Plenary Lecture at the *1995 Midwest Mechanics Symposium*, University of Iowa, Ames, IA (October 2, 1995).
3. "Synergistic Diagnostics of Aircraft Materials and Structures", *Structural Mechanics Workshop*, (AFOSR Review), Virginia Beach, VA (June 25, 1996).
4. "Synergetics of Measurement, Prediction and Control", Invited Plenary Lecture at the *1996 Gordon Research Conference - Nondestructive Evaluation*, Meriden, NH (August 19, 1996).
5. "Synergetics of Measurement, Prediction and Control", Invited Lecture to the Slovenian Academy of Sciences, Ljubljana, Slovenia (May 8, 1997).
6. "Predictive Measurement Using AE: Fracture and Lifetime of Al-alloys", *8th International Symposium on Nondestructive Characterization of Materials*, Boulder, CO (June 18, 1997).
7. "Automatic Modeling for Acoustic Source Location", *Ultrasonics International'97*, Delft, Holland (July 3, 1997).
8. "Synergistic Diagnostics of Aircraft Materials and Structures", *Intelligent NDE Sciences for Aging and Futuristic Aircraft*, FAST Center for Structural Integrity of Aerospace Systems, University of Texas, El Paso, El Paso, TX (October 1, 1997).