FLIGHT PARAMETERS MONITORING SYSTEM FOR TRACKING STRUCTURAL INTEGRITY OF ROTARY-WING AIRCRAFT

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SUMMARY

Recent developments in advanced monitoring systems used in conjunction with tracking structural integrity of rotary-wing aircraft are explained. The paper describes: (i) an overview of rotary-wing aircraft flight parameters that are critical to the aircraft loading conditions and each parameter's specific requirements in terms of data collection and processing; (ii) description of the monitoring system and its functions used in a survey of rotary-wing aircraft; and (iii) description of the method of analysis used for the data. The paper presents a newly-developed method in compiling flight data. The method utilizes the maneuver sequence of events in several pre-identified flight conditions to describe various flight parameters at three specific weight ranges.

INTRODUCTION

Flight data monitoring has proven to be an effective method for the evaluation of structural integrity of aircraft. A successful monitoring program requires a comprehensive effort involving data gathering, analysis and engineering evaluation and interpretation of all parameters that influence the aircraft loading conditions. Specifically, the flight parameters data in the form of time history and/or frequency of occurrence of peaks and valleys are needed for implementation in the analysis of structural integrity of the aircraft. Examples of such parameters include the normal acceleration (N_Z), roll, pitch, gross weight, rotor speed, etc. During a flight operation, an immense amount of data on the flight parameters is gathered so that nearly all possible values of the key parameters, that influence the load conditions of the aircraft, can be captured. This calls for an advanced system capable of (i) handling the volume of incoming flight data, and (ii) processing the data on a real-time basis.

This paper focuses on recent developments in advanced monitoring systems used in conjunction with tracking structural integrity of rotary-wing aircraft. In particular, the paper describes the experiences of Systems & Electronics, Inc. (SEI) in design and application of such systems. The paper presents: (i) an overview of rotary-wing aircraft flight parameters that are critical to the aircraft loading conditions and each parameter's specific requirements in terms of data collection and processing; (ii) description of SEI's monitoring system and its functions. This includes the system's operational capabilities and recording capacity; and, (iii) description of the method of analysis used for the data. In this regard, the paper describes that the analysis is partially done by the recorder on a real-time basis. Additional processing and development of flight parameters histories, maneuver recognition, flight maneuver sequence of events and frequency of occurrence of peaks and valleys of key parameters are performed upon downloading the recorder onto a personal computer.

PART 2

The research has been in progress for the past three years. With the current system in operation, flight data aboard several aircraft types are being compiled and processed. The paper specifically discusses that: (i) Flight maneuver sequence of events recording, as adopted in this project, provides a detailed information on aircraft various operations during the flight. This also allows for recording of various key flight parameters at each flight condition and at each event; (ii) Development of a built-in data quality assurance procedure provides a means to verify the expected ranges of flight parameters. To a limited extent, this procedure is effective in identifying problem areas that may occur during the data acquisition process; and (iii) The processed data can be used as an input to development of a comprehensive structural integrity evaluation. The peak and valley data and the item-by-item sequence of events data recording are specially helpful in tracking the structural integrity of the aircraft in a more refined manner by identifying flight conditions that are more severe to the aircraft structure.

The paper also presents samples of aircraft data compiled and processed via SEI's system.

AIRCRAFT FLIGHT PARAMETERS

The selection of flight parameters depends on the type of aircraft and the configuration of its structural components. Furthermore, the selection of desired parameters depends on the flight condition for which the data is being compiled. A multi-parameter data acquisition system is used and configured to accommodate the aircraft's requirements and intended flight conditions. Flight parameters selected in the survey of CH-46 and AH-1W aircraft are described in this paper.

In the CH-46 application, twenty (20) parameters were selected for the survey by SEI. These parameters are: (1) normal acceleration; (2) roll angle; (3) pitch angle; (4) heading angle; (5) rotor RPM; (6) outside air temperature; (7) longitudinal speed; (8) rudder pedal position; (9) weight on wheels; (10) rotor brake; (11) collective stick position; (12) airspeed; (13) altitude; (14) fuel quantities (left and right); (15) cruise guide indicator; (16) lateral speed (doppler); (17) engine torques (left/right); (18) cargo hook strain; (19) longitudinal stick position; and (20) lateral stick position.

The system employed to monitor CH-46 consists of the following equipment:

- Recorder Converter, RD-601/ASH-37 (RC)
- Memory Unit, MU-983/ASH-37 (MU)
- Motional Pick-up Transducer, TR-354/ASH-37 (MPT)
- Signal Data Converter, CV-4193/ASH-37 (SDC)
- Data Entry Keyboard, KY-941/ASH-37 (DEK)
- Temperature probe for the outside air temperature
- Recorder Reproducer, RD-608/ASH-37 (RR)

The Recorder Converter, Memory Module and Motional Pick-up Transducer make up the components of the structural data recording set (SDRS). Figure 1 shows the process of data acquisition using SDRS.

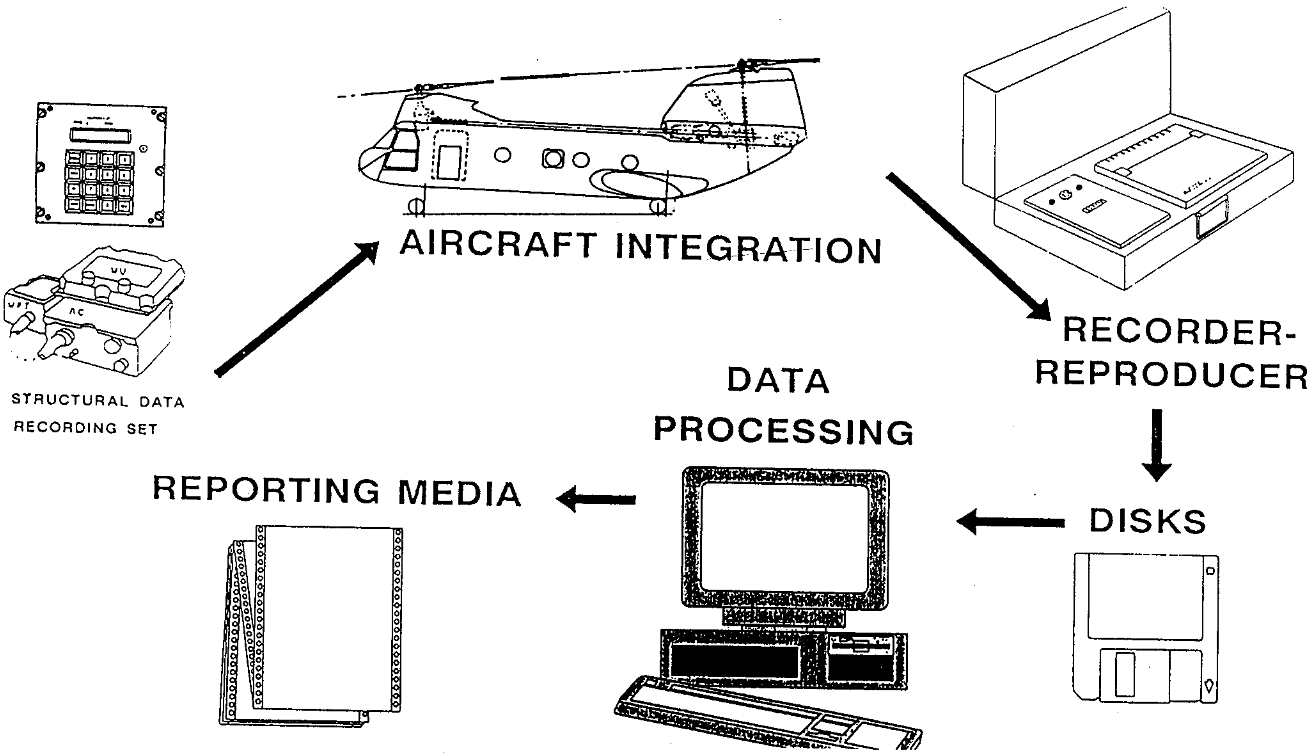

Fig. 1 SDRS Recording Procedure

The CH-46 aircraft parameters were acquired as follows:

1) Normal acceleration was obtained from the MPT which was installed on floor board at FS 254.

2) Air data (pitot and static pressure) was obtained from the aircraft pitot, static system. These pressures were then supplied to the pressure transducers internal to the RC and aircraft. The indicated airspeed and altitude values were derived from these pressures.

3) Roll angle, pitch angle and heading were obtained from the aircraft attitude heading reference system. These signals were then conditioned by the SDC and supplied to the RC.

4) Rotor RPM was obtained from the aircraft rotor tach generator. This signal was then conditioned by the SDC and provided to the RC.

5) Left and right engine torques were obtained from the co-pilot's torque indicator. These signals were conditioned in the SDC and then supplied to the RC.

6) Outside air temperature (OAT) was obtained from the OAT probe installed on the forward left side of the aircraft.

7) Pedal, longitudinal stick, lateral stick and collective stick positions signals were obtained from the roll, pitch and yaw control and collective stick transducer. These signals were conditioned by the SDC and then input into the RC.

8) The cruise guide indication was obtained from the cruise guide indicator located in the cockpit. This signal was conditioned by the SDC and input into RC.

9) The lateral and longitudinal velocities were obtained from the radar navigation set, AN/APN-21F. These signals were conditioned by the SDC and then input into the RC.

10) The right and left tank fuel quantities were obtained from the cockpit fuel quantity indicator. These signals were then combined to provide a total fuel quantity signal by the SDC and then input into the RC.

11) The external load was obtained from a strain sensor mounted to the external cargo hook. This signal was conditioned by the SDC and then input to the RC.

12) The weight-off-wheels signal was obtained from the left main gear squat switch. This signal was conditioned by the SDC and then input to the RC.

13) The rotor brake signal was obtained from the rotor brake and blade fold control box. This signal was conditioned by the SDC and input into the control box. The signal was then conditioned by the SDC and supplied to the RC.

In the AH-1W application the flight parameters recorded are mainly the same as those in the CH-46 application. Among these parameters included (1) the normal acceleration, (2) airspeed, (3) roll and pitch attitudes, (4) engine torque, (5) rotor speed, (6) lateral and longitudinal stick positions, (7) pedal position, and (8) rate of descent. Figure 2 shows the data acquisition block diagram in the AH-1W application.

PROCESSING THE DATA

The processing of the data is partially performed by the recorder. Additional analyses are then performed upon downloading the data onto a PC. The data recording process used in RC is a maneuver recognition algorithm. Using this algorithm, all input parameters to the SDRS are monitored for identification of various sequence of events and specific maneuvers experienced by the aircraft during the flight. The sequence of events that define a maneuver is determined from the flight spectrum specified by the aircraft manufacturer. In the AH-1W application, a total of 293 uniquely definable flight conditions were incorporated in the RC data processing algorithm. Each defined flight condition is, in turn, separated into three gross weight ranges. These are:

- The low weight range defined by a gross weight of less than 12,500 lbs;
- The medium range defined by a gross weight of between 12,500 and 13,500 lbs; and,
- The heavy weight range defined by those in excess of 13,500 lbs.

Table I presents two samples of the sequences of events that uniquely identify a specific

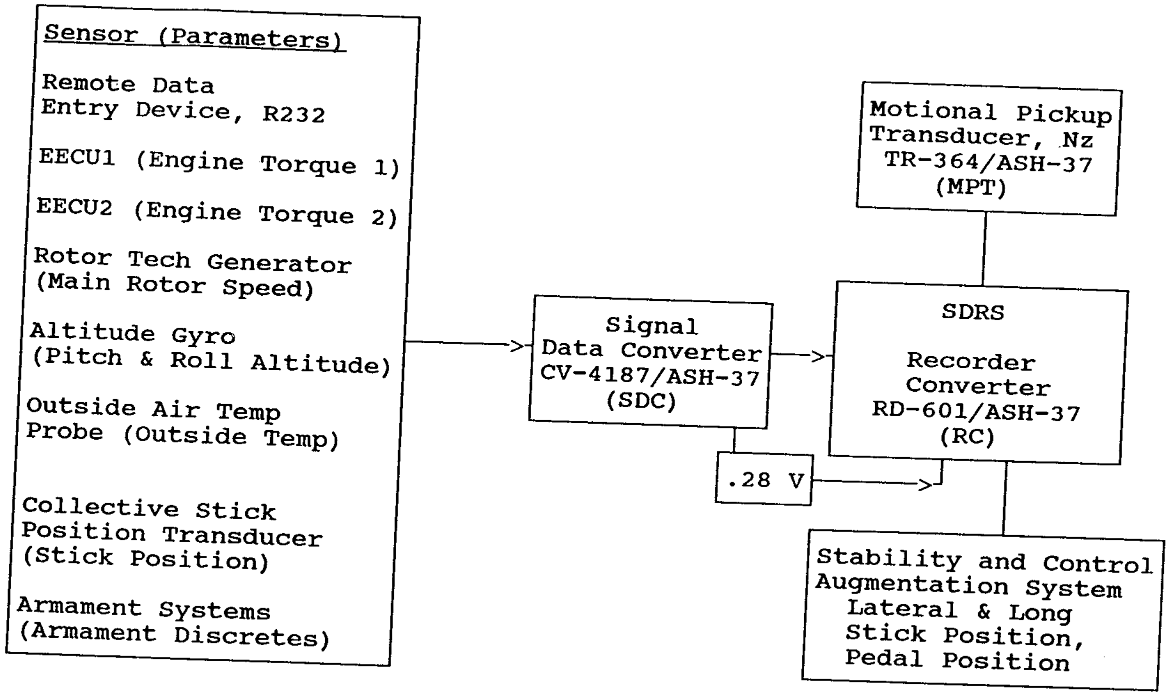

Fig. 2 AH-1W SDRS Block Diagram

maneuver in the AH-1W application. A similar process is also adapted in the CH-46 application. However, this process can be tailored to meet the specific data acquisition needs of each type of aircraft.

The SDRS executes the maneuver recognition algorithm on a real-time basis starting from aircraft power up to power down. The final product at the conclusion of each operation is a complete history of the flight with (i) the time of occurrence of each maneuver; (ii) the time spent in each maneuver; and (iii) the values of all parameters that show a change. Furthermore, the weight ranges in which the maneuver occurs is identified and marked. If a flight condition that is not previously defined is encountered, the system automatically assigns an "unrecognized mode" recording. Simultaneously, the system logs a record of each flight parameter's band, thereby compiling the data on the parameter's range. Each time a parameter's value changes into a new band, the system logs the parameter that experienced the change and the corresponding new band value. This type of recording continues until one of several pre-identified built-in "recognized" flight conditions is encountered.

The data compiled for an unrecognized mode of recording provides a detailed description of those flight parameters that are significantly affected. If an unrecognized mode is repeated over a period of time, then the system will treat the mode as a new flight regime and will add it to the aircraft's flight spectrum.

At the conclusion of each flight data acquisition session, the compiled data is summarized describing the period of time spent (i) in each flight regime pre-defined by the aircraft's flight spectrum, and (ii) in regimes labeled as unrecognized modes. For certain flight parameters, additional analyses and data summary can also be conducted to suit the specific requirements by a given type of aircraft. For example, in most applications, the frequency of various levels of the normal acceleration (N_Z) encountered during the flight is desired. Such data include the number of times a specific N_Z level has been experienced either as a peak or valley acceleration. The system can also be configured to adopt any desired cycle counting method for this purpose. The current algorithm is based on counting the rising and dropping N_Z (peaks) or dropping and rising N_Z (valley) as it crosses various thresholds predetermined and built in the system. Other cycle counting algorithms (ref. 1) including the ASTM rainflow method (ref. 2) can easily be configured and implemented in the system.

With current applications, more than thirty flight hours of data are typically recorded in less than 100K bytes of nonvolatile memory. Samples of AH-1W data are presented in Table II.

DATA QUALITY ASSURANCE

To assure the quality of the incoming data on a continuous basis, a rigorous program of data inspection and analysis will be needed. As it is expected, flight data are subject to variations. The purpose of the quality assurance (QA) procedure adopted for use in conjunction with the flight parameters data acquisition of rotary-wing aircraft is merely to limit these variations to those that arise from such factors as:

- Uncertainty associated with the method of data acquisition process. Marginal errors in predicting various thresholds and bands for flight parameters are among uncertainties inherent in the method of data acquisition process. In most parts the estimates for a flight parameter's bands are derived on the basis of the aircraft's previous flight records which are subject to variabilities.

- Errors associated with various sensors' sensitivities.

- Marginal errors encountered during installations, initial readings, tests and calibrations.

The QA procedures are intended to provide a safeguard against recording erroneous data that generally do not fall within the expected norms. Although a total elimination of errors is not feasible, certain measures can be taken to minimize their occurrence and recurrence during the data acquisition process. The QA process adopted in the flight survey of aircraft is a three-step procedure. The first step is conducted by the system as a self-test type of approach. The second step consists of a rigorous statistical analysis of the data to establish data trends and to identify any discrepancies in the data that may be an indication of a potential deviation from the norms. The final step involves the identification of the source of the problem and development of an appropriate corrective measure to remedy the potential problem areas. Figure 3 presents a schematic diagram of the QA procedure activities. A brief description of the three steps involved in the QA procedure is provided below.

As described earlier, the system is initially introduced with several pre-identified flight conditions. As the data compilation continues, the system recognizes the occurrence of these pre-defined flight conditions. The values of the flight parameters within each flight condition are regularly checked against the expected limits. Any discrepancies are flagged for further investigations. If the system does not recognize a flight condition, with all parameters being within their respective acceptable ranges, a new flight condition will be added provided that the unrecognized condition is repeated (as described earlier). This constitutes Step 1 in the QA process.

As flight data are compiled, batches of data are selected for detailed statistical analyses. The purpose of such analyses is to investigate:

- Any statistical correlation that is expected between two or more parameters.
- A trend or pattern in the distribution of a parameter or groups of parameters.
- Consistency among blocks of data compiled for a given flight parameter for the same aircraft or for several identical aircraft.
- Consistency of the data when compared with published results, design values and norms indicated in the aircraft's manual.

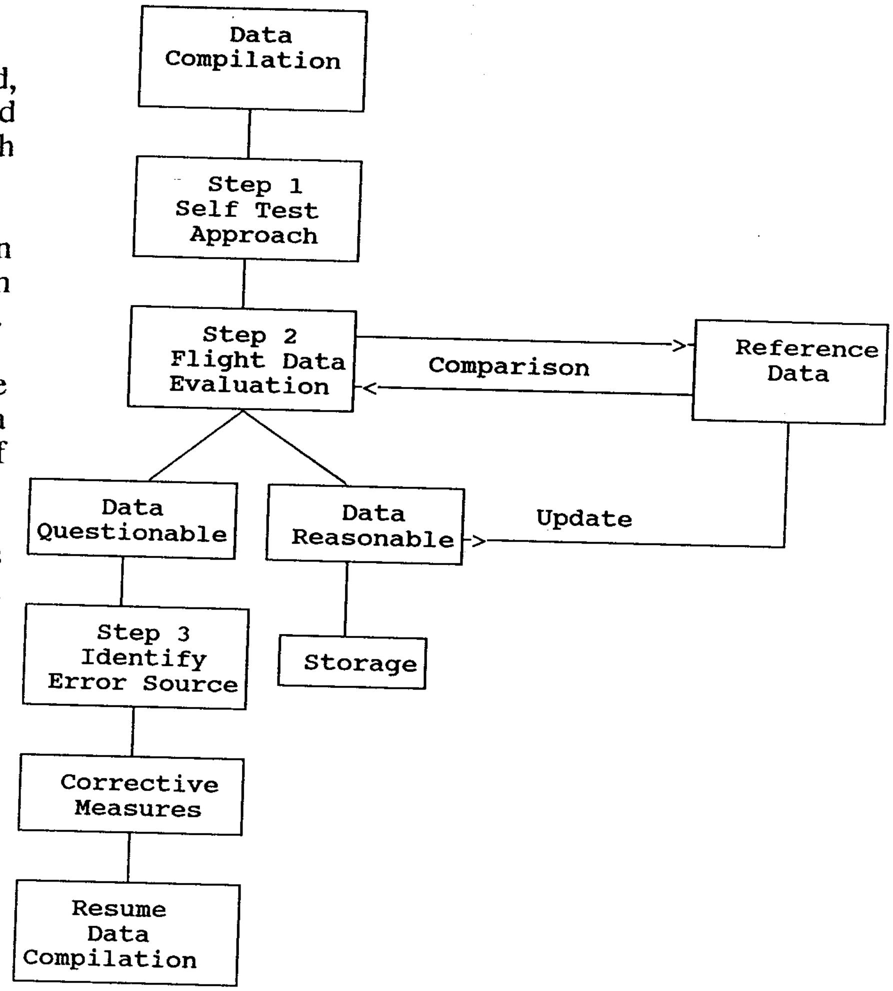

Fig. 3 Flight Data QA Procedure

An inventory of qualified data or published results are maintained for a reference. The reference data is periodically updated and revised, if necessary, as new data becomes available. Dramatic changes occurring in the data are carefully investigated to identify any potential problem area associated with the data acquisition process. This constitutes Step 2 in the QA process.

Corrective measures are taken only if a problem area has been identified and proven to be the source of error or dramatic change in the data. Appropriate measures could consist only of a few adjustments in the previously-selected expected thresholds for a parameter; a re-calibration of sensors; an added feature to the previously-identified flight conditions; a replacement of a faulty sensor; a reconfiguration of the system; or replacement of the data acquisition system. In most applications the replacement of a sensor or the entire data acquisition system is rarely needed. Most often the problem area can be corrected with a few changes in the system configuration. This constitutes Step 3 in the QA procedure.

MONITORING AIRCRAFT STRUCTURAL INTEGRITY

A major application of the results of aircraft flight surveys is in tracking the structural integrity of the aircraft. This section briefly discusses the process via which the structural integrity evaluation of the aircraft can be achieved using flight data. No specific method has been established by SEI for this purpose. The following discussion is intended only for describing the effort needed to develop a method for evaluating the integrity of the airframe structure based on the type of flight data compiled for rotary wing aircraft.

The peak and valley statistics compiled for the normal acceleration are crucial to the structural analysis of the aircraft. These statistics provide the input data needed for estimating the damage induced in various structural components of the aircraft. The peak and valley statistics of N_Z constitute the distribution of the frequency of load application on the structure. These statistics can be used directly to estimate the remaining useful life of various critical components of the aircraft. In this regard, the aircraft manufacturer's data on the damage tolerance of a given structural component will then be needed and used along with the load statistics to estimate the damage accumulated by the component as a result of the load applied for the duration of flight for which the load data was compiled. In rotary wing aircraft, the damage tolerance data is often described in terms of the total number of load cycles of specific ranges needed to cause a complete failure of the component.

Alternatively, the load data can be used in a detailed structural analysis of the aircraft to arrive at stress distributions at a critical structural component. This information can then be used along with the fatigue or fracture mechanics approach to arrive at the damage accumulated by the component and thus to estimate the remaining useful life of the component. This method has been mainly used in other types of structures (ref. 3) and especially to fixed wing aircraft. The basic requirement for this method is that the fatigue characteristics of the component in the form of S-N relation (stress versus the number of load cycles to failure) be known so that a crack initiation analysis can be conducted. If a crack growth analysis is the method of choice, then crack growth characteristics of the structural component will be needed (see, for example, refs. 1 and 4). Such data for various structural components can be found in ref. 5. The data in ref. 5, however, has been mainly used in fixed wing aircraft applications.

The flight maneuver sequence of events compiled for rotary wing aircraft, as described in this paper, provide the data on specific flight conditions. This type of data is especially useful in identifying the damage potentials of the applied load at various operations during the flight. The data specific to each operation can be used to estimate the percent of a component's life expended as a result of that flight operation. This information is critical to the structural integrity of the aircraft and development of a more efficient planning for inspection and maintenance of the aircraft. The data is especially useful to ascertain the significance of various flight operations on tear and wear of structural and mechanical components of the aircraft.

CONCLUSIONS

The process of flight data acquisition for rotary wing aircraft is explained in this paper. The paper describes various elements of this process and the type of flight data compiled in conjunction with tracking the structural integrity of aircraft. The presented method groups flight data in three weight categories and lists them by a series of pre-identified flight conditions (regimes). Major conclusions of the study are:

- The item-by-item sequence of events data recording is helpful in providing a more refined and more descriptive way of summarizing the flight data.

- The self-test mechanism and automatic upgrading of flight spectrum as conducted by the data acquisition system are features that are especially helpful in assuring the quality of the incoming flight data.

- The system offers an efficient mechanism to compile up to 30 hours of flight data in one download. An ample amount of information on the aircraft parameters is acquired and summarized by the system in each flight.

- The results of the survey using the system described in this paper can be used as an input to a comprehensive structural tracking program for rotary wing aircraft.

It is anticipated that the results of this study will enhance the process of tracking the structural integrity of rotary-wing aircraft. Possible future research in this area is expected in automated condition assessment of aircraft structural components and estimation of their potential accumulated damage on a flight-by-flight basis. An advanced system capable of conducting the needed structural analysis should have a built-in module containing the fatigue properties of critical structural components. Furthermore the system will need a direct communication link with the current SEI's monitoring system so that it can receive the flight data for the purpose of structural analyses.

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5. Gallagher, J.P., et al, *USAF Damage Tolerant Design Handbook, Rept. #AFWA L-TR-82-3073,* University of Dayton Research Institute, Dayton, OH, May 1984.

TABLE I Samples of AH-1W Sequence of Events

MANEUVER	PARAMETER RANGES	SEQUENCE OF EVENTS
NORMAL TURN @ 0.7 Vh	$1.3g \leq N_z < 1.8g$ 0.55Vh ≤ AIRSPEED < 0.75 Vh ROLL ATTITUDE > |10°| -500 FEET PER MINUTE ≤ RATE OF DESCENT < 500 FEET PER MINUTE. -35° < PITCH ATTITUDE < 35°. ENGINE TORQUE 1 < 405 FT. -LBS. ENGINE TORQUE 2 < 405 FT. -LBS. MAIN ROTOR SPEED < 326 RPM. 0% ≤ LATERAL STICK POSITION < 100%. 0% ≤ LONGITUDINAL STICK POSITION < 100%. 0% ≤ PEDAL POSITION < 100%. COLLECTIVE STICK POSITION > 10%.	ROLL ATTITUDE EXCEEDS 10° ANGLE OF BANK. THEN N_z EXCEEDS 1.3g BUT DOES NOT EXCEED 1.8g. THEN N_z GOES BACK BETWEEN 1g AND 1.3g. THEN ROLL ATTITUDE GOES LESS THAN 10° ANGLE OF BANK. THEN YOU WAIT FOR POSSIBLE SUBSEQUENT ROLL EXCURSIONS. WHEN THEY ARE COMPLETED THE TURN IS OVER. LOG AMOUNT OF TIME IN TURN AND ENTER A NEW REGIME.

TABLE I (continued)

AIRCRAFT: AH-1W MANEUVER	PARAMETER RANGES	SEQUENCES OF EVENTS
STRAIGHT AND LEVEL FLIGHT 0.5 Vh	$0.5g \leq N_z < 1.3g$ 0.4 Vh ≤ AIRSPEED < 0.55 Vh ROLL ALTITUDE < |10°| -500 FEET PER MINUTE ≤ RATE OF DESCENT < 500 FEET PER MINUTE. -13° ≤ PITCH ATTITUDE < 7° 30 FT. -LBS. ≤ ENGINE TORQUE 1 < 405 FT. -LBS. 30 FT. -LBS. < ENGINE TORQUE 2 < 405 FT -LBS. MAIN ROTOR SPEED < 326 RPM 0% ≤ LATERAL STICK POSITION < 100% 0% ≤ LONGITUDINAL STICK POSITION < 100% 0% ≤ PEDAL POSITION < 100% COLLECTIVE STICK POSITION > 10%	IF THIS COMBINATION OF PARAMETER VALUES OCCURS FROM ANY OTHER FLIGHT REGIME THEN THIS REGIME IS ENTERED.

TABLE II Samples of AH-1W Flight Data

Peak Nz Counts:		Valley Nz Counts:	
-1.00g to -0.75g	0	-1.00g to -0.75g	0
-0.75g to -0.50g	0	-0.75g to -0.50g	0
-0.50g to -0.25g	0	-0.50g to -0.25g	0
-0.25g to 0.00g	0	-0.25g to 0.00g	0
0.00g to 0.25g	0	0.00g to 0.25g	0
0.25g to 0.50g	0	0.25g to 0.50g	6
0.50g to 0.75g	4	0.50g to 0.75g	0
0.75g to 1.00g	3	0.75g to 1.00g	0
1.00g to 1.25g	0	1.00g to 1.25g	0
1.25g to 1.50g	0	1.25g to 1.50g	0
1.50g to 1.75g	0	1.50g to 1.75g	0
1.75g to 2.00g	0	1.75g to 2.00g	0
2.00g to 2.25g	0	2.00g to 2.25g	0
2.25g to 2.50g	0	2.25g to 2.50g	0
2.50g to 2.75g	0	2.50g to 2.75g	0
2.75g to 3.00g	0	2.75g to 3.00g	0
3.00g to 3.25g	0	3.00g to 3.25g	0
3.25g to 3.50g	0	3.25g to 3.50g	0
3.50g to 3.75g	0	3.50g to 3.75g	0
3.75g to 4.00g	0	3.75g to 4.00g	0
4.00g to 4.25g	0	4.00g to 4.25g	0
4.25g to 4.50g	0	4.25g to 4.50g	0
> 4.5g	0	> 4.5g	0

####	FCC	ELAP. TIME	MANV. TIME	FCC DESCRIPTION	ROTOR	ALTITUDE
1	267	00:02:38.1		Rotor Start/Stop (Low wgt)	280<rtr<295	alt<3k
2	0	00:09:36.7		Normal Takeoff (Low wgt)	295<rtr<326	alt<3k
3	6	00:09:53.2	00:00:16.5	Steady Hover (Low wgt)	295<rtr<326	alt<3k
4	51	00:09:56.1	00:00:02.9	Forward Flt < .3Vh (Low wgt)	295<rtr<326	alt<3k
5	562	00:10:00.1	00:00:04.0	Asc Hover/Forward Flight below .3 VH (Low wgt)	295<rtr<326	alt<3k
6	51	00:10:03.2	00:00:03.1	Forward Flt < .3Vh (Low wgt)	295<rtr<326	alt<3k
7	261	00:10:03.2		Normal Landing (Low wgt)	295<rtr<326	alt<3k
8	3	00:12:12.6		Jump Takeoff (Low wgt)	295<rtr<326	alt<3k
9	562	00:12:18.1	00:00:05.5	Asc Hover/Forward Flight below .3 VH (Low wgt)	295<rtr<326	alt<3k
10	6	00:12:49.1	00:00:31.0	Steady Hover (Low wgt)	295<rtr<326	alt<3k
11	532	00:12:50.1	00:00:01.0	Desc Hover/Forward Flight below .3 VH (Low wgt)	295<rtr<326	alt<3k
12	6	00:12:52.1	00:00:02.0	Steady Hover (Low wgt)	295<rtr<326	alt<3k
13	562	00:12:54.1	00:00:02.0	Asc Hover/Forward Flight below .3 VH (Low wgt)	295<rtr<326	alt<3k
14	6	00:13:21.1	00:00:27.0	Steady Hover (Low wgt)	295<rtr<326	alt<3k
15	562	00:13:23.1	00:00:02.0	Asc Hover/Forward Flight below .3 VH (Low wgt)	295<rtr<326	alt<3k
16	6	00:13:46.6	00:00:23.5	Steady Hover (Low wgt)	295<rtr<326	alt<3k
17	51	00:13:47.4	00:00:00.8	Forward Flt < .3Vh (Low wgt)	295<rtr<326	alt<3k
18	36	00:13:49.0	00:00:01.6	Left Sideward Flt (Low wgt)	295<rtr<326	alt<3k
19	370	00:13:49.8	00:00:00.8	Low Speed Maneuver below .3 VH (Low wgt)	295<rtr<326	alt<3k
20	51	00:13:50.1	00:00:00.3	Forward Flt < .3Vh (Low wgt)	295<rtr<326	alt<3k
21	532	00:13:52.1	00:00:02.0	Desc Hover/Forward Flight below .3 VH (Low wgt)	295<rtr<326	alt<3k
22	832	00:13:53.9		Maximum Band Threshold Crossing (Low wgt) Offending Value(s): ROT - 4		