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A EXPERT SYSTEM TO ANALYZE HIGH FREQUENCY DEPENDENT DATA FOR THE SPACE SHUTTLE MAIN ENGINE TURBOPUMPS

PREPARED
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ABSTRACT

A prototype expert system (named ADDAMX) is being developed using a rule induction expert system development tool, EX-TRAN 7.0. ADDAMX will analyze graphically represented rotordynamic high frequency dependent data from the low and high pressure liquid hydrogen (fuel) and liquid oxygen (LOX) turbopumps on the Space Shuttle Main Engine. It infers the operation of the turbopumps by using knowledge from an expert coded into rules to analyze Spectral Data. ADDAMX infers the turbopumps operation by identifying the speed frequencies and harmonics from each respective turbopump, the frequency feed through from one turbopump to another, the bearing generated frequencies from the pump and turbine end of the turbopumps and the pseudo and super pseudo 3N frequencies from the phase two High Pressure Fuel Turbopump (HPFTP).

1.0 INTRODUCTION

Analysis of rotordynamic high frequency dependent data is a team effort and time consuming manual procedure. The Automated Dynamic Data Analysis and Management system (ADDAM) will process and graphically represent the high frequency dependent data. This will significantly reducing the processing time; however, the analysis of the data will continue to be time consuming. This bottleneck is a result of the quantity of graphs and data routinely analyzed. To further complicate the dilemma, the knowledge to analyze the data reside in a few expert analysts; therefore, the routine and challenging analysis of data are further bottlenecked.

2.0 OBJECTIVE

The objective of the project is to develop a prototype expert system using a rule induction FORTRAN based expert system development tool called EX-TRAN 7.0. The Automated Dynamic Data Analysis and Management Expert System (ADDAMX) will analyze graphically represented high frequency dependent data, in the form of Power Spectral Density Plots (PSD), collected from strategic points of measurement on the Space Shuttle Main Engine (SSME) turbopumps. ADDAMX will identify the source of specific sinusoids which are indicative of the turbopumps operation using domain-specific knowledge, analysis techniques, rules of thumb acquired during interviews with the expert analyst and knowledge from documents approved by the expert analyst. The results of the analysis will be shared with the nonexpert or expert user (relative to the subject matter) in an effective manner.

3.0 KNOWLEDGE ACQUISITION

The theory of data acquisition, data representation, data interpretation and communication within the rotordynamic arena must be understood by the author (knowledge engineer) and the reader. Two methods to gain an understanding of the data were used; the first is reading two documents which give a good comprehensive overview of the data and the second is interviewing the expert. The first document is the "Rotordynamics High Frequency Dynamic Data Summary Book SSME Turbomachinery". This is an in-house proprietary document generated by experts in the field. The second document is Application Aote 243, "THE FUNDAMENTAL OF SIGNAL ANALYSIS", a document prepared by Hewlett Packard. Using both of these documents one can begin to understand data and the language used by the expert analyst.

The second part of understanding data included interviewing the expert. The task of analyzing data is divided amongst several people who work as a team. Identification of each team player's task is important. Several lengthy sessions with the expert were held to discuss the theory of data acquisition, data representation, data interpretation and the analyzing team's structure. The interview process usually consisted of a one hour session where the author asked questions of the expert. The response usually prompted additional questions relative to the subject. After the interview the acquired knowledge, "rules of thumb" and "tricks of the trade" were reduced to a written form, then presented to the expert at the next session for review and corrections. This continuous transfer and check process assured an accurate transfer of knowledge.

The identification of the specific duties and responsibilities of the expert and the associates helped to divide the process into steps which would later help structure the expert system. Each associate was interviewed to obtain his knowledge for the particular task he performed. Keep in mind the associates can be considered experts in their particular task; however, relative to the project they are referred to as associates.

Occasional conflicts of theory or the process of analyzing data were resolved by asking the expert to clarify the theory or process to both the knowledge engineer and the associate. This way an open communication and consistent application of the knowledge was assured. The expert had the final say in the conflict.

3.1 DATA MANAGEMENT

High frequency data is recorded onto magnetic tapes during hot fire and flight SSME engines from strategically located accelerometers on the low and high pressure liquid hydrogen (fuel) and liquid oxygen (LOX) turbopumps, preburners and the preburner pump. Thrust level of the engine and the venting and/or pressurization of the fuel and LOX tanks is also recorded. The tapes are delivered to the appropriate real-time data analysis (RTDA) labs where data is digitized and then displayed on graphs used by the Data Analyst to infer the operation of the turbopumps. The ADDAM system is specially designed to display data in several types of graphs.

The team reviews the graphs to identify "expected events" indicating the nominal operation of the turbopumps. The team identifies events which need more analysis. These latter events are referred to as anomalies and may indicate non-nominal operation of a particular turbopump.

4.0 KNOWLEDGE REPRESENTATION

The creative aspect of representing the knowledge obtained from the expert and the associates proved to be the most challenging part of the project. Several methods and schemes were attempted until the present one was adopted.

The terms used in the sections to follow are obtained from the theory and nomenclature in the EX-TRAN 7.0 user manual, June 1984, documented by Mohammed A-razzak and Thamir Hassan, Intelligent Terminal LTD., U.K. [reference 3].

A main problem is the object in question or the problem to be solved. The main problem can be divided into subproblems each with its unique or common attributes. The attribute's values, numeric or symbolic, combined in certain ways (examples) will give the subproblems unique values which contribute to the solution of the main problem. The arguments determine the value of the attribute and are obtained by special subroutines which get the value from the ADDAM system.

4.1 EXPERT SYSTEM IMPLEMENTATION

ADDAMX is divided into 2 modules. The first is a "batch mode" module where analysis of the PSD plots is executed automatically. A PSD graph plots the power spectral density in G's squared per hertz versus frequency in hertz at a selected time slice. Events on the PSD plot are identified directly on the PSD plot hardcopy. No explanation is given of how the results are obtained (see figure 4.1). The second module is a "user interactive" module where the common expert system features of explanation of analysis behavior is possible. This module has received less priority then the batch module because of the need of the batch module. The concepts presented are implemented into both modules.

The main problem for the interactive module of ADDAMX is divided into eight subproblems (see figure 4.2). Attributes within subproblems can have several different values. The main problem for the batch module of ADDAMX uses five subproblems (see figure 4.3). These five subproblems use the same attributes as the above eight subproblems and do the same analysis.

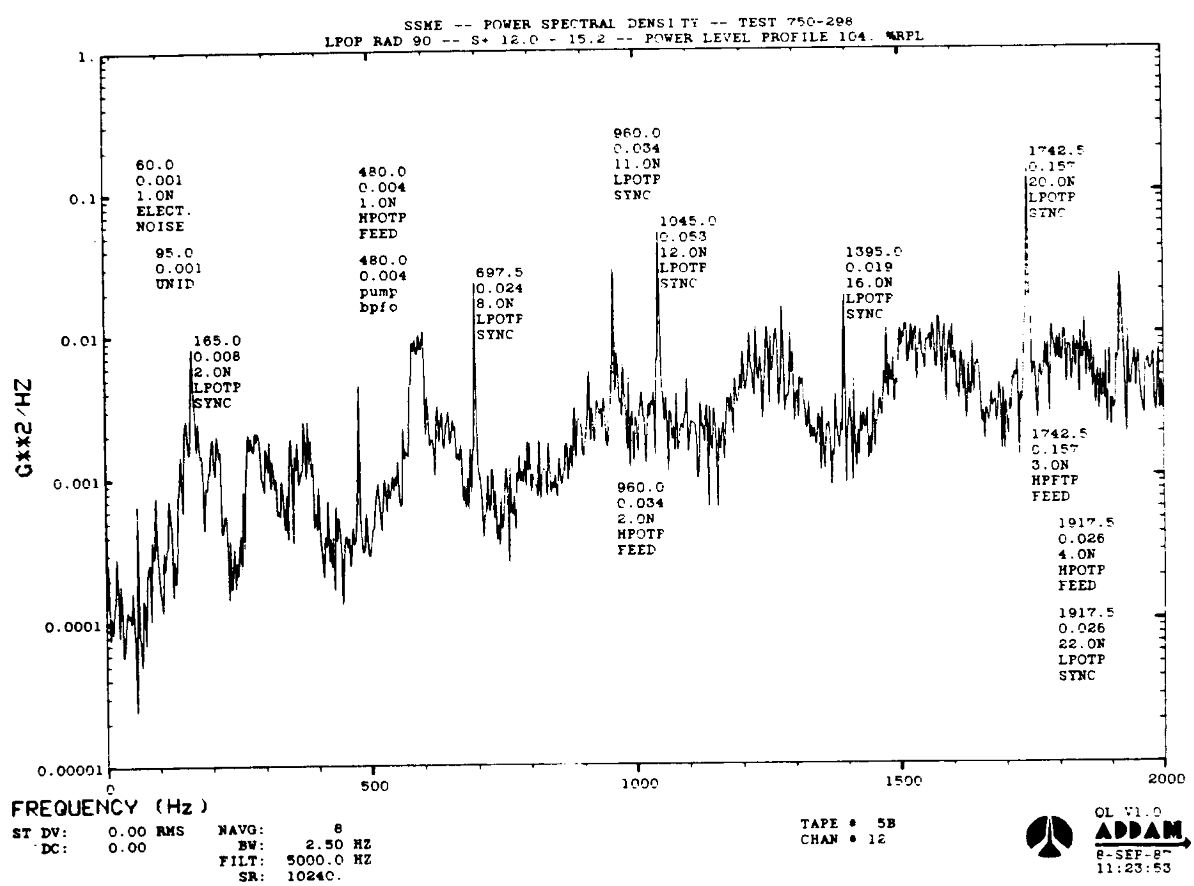

Figure 4.1: Batch module hardcopy output.

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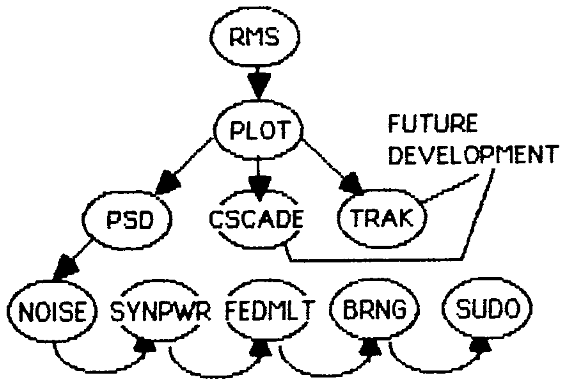

Figure 4.2: ADDAMX interactive subproblem flow chart.

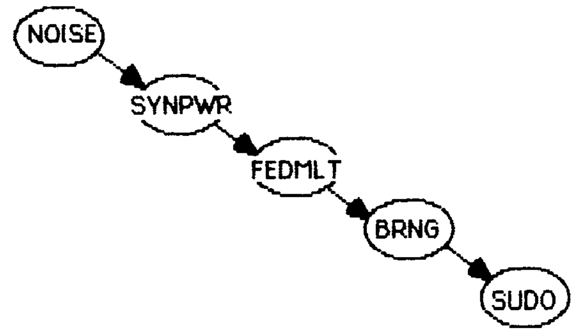

Figure 4.3: ADDAMX batch subproblem flow chart.

The ADDAMX interactive module uses two types of subproblems: "control subproblems" and "analysis subproblems". These names are unique to this project and may not be found in other literature. The control subproblems are "RMS", "PLOT", and "PSD". These subproblems control the execution of the other subproblems by directing the flow to the appropriate branch of the tree as shown in figure 4.2. The above subproblems do not directly analyze data to infer the turbopump's operation. For example, subproblem "PLOT" directs the flow of analysis to the appropriate knowledge base identified with the graph to be used to infer the turbopump operation. Each graph has its own knowledge base which deals with the graph's attributes and variables.

The analysis subproblems are "NOISE", "SYNPWR", "FEDMLT", "BRNG" and "SUDO". These subproblems analyze data directly to infer the turbopumps operation. FORTRAN IF-THEN rules are generated using an extension of Quinlan's ID3 algorithm (see Michalski, Carbonell and Mitchell, 1983) from examples obtained and derived from the knowledge aquired. The "noise" subproblem analyzes a sinusoid for the selected PSD measurement to determine if it is not indicative of a known non-turbopump frequency generating source; for example, a sixty hertz electrical cycle. Subproblem "SYNPWR" contains the knowledge for identifying a sinusoid as a speed synchronous or multiple of speed synchronous frequency for the appropriate turbopump. Subproblem "FEDMLT" identifies sinusoids which feed from one turbopump to another through the ducts, pipings and supports. Subproblem "BRNG" analyzes the sinusoid for possible origin from a turbopump pump or turbine bearing generating source. Subproblem "SUDO" analyzes the sinusoid in question to determine if it may be identified as a pseudo 3n or super pseudo 3n event.

If the sinusoid is not identified as one of the above five types of known sources of sinusoid generation then the attributes and sinusoid frequency values are written to a history file called

"HISTORY.DAT". As the system matures, more knowledge will be added to the knowledge base thus increasing the probability of identifying more expected and unknown sinusoids.

The analysts use table 4.0 as a guideline to help them identify operating windows for the turbopumps speed synchronous frequency. A window is a range above and below the mean value in which a known sinusoidal is expected to be found. The lower and upper bound for the window is obtained from a shaft speed versus power level graph. Because the new design turbopumps operate at lower speeds the window is not symmetrical about the mean; therefore, the lower bound is several hertz lower than expected. Furthermore, the lower and upper bound are not a statistical value but a guideline the analyst uses; therefore, ADDAMX, being an expert system, uses this guideline as such. Of course the integer multiples of the mean with the corresponding range shown on the table are used to identify the different multiples of speed synchronous frequency.

POWER LEVEL %	HPOTP -20 +15	HPFTP -20 +10	LPFTP -20 +15	LPOTP -10 +5
65	320	450	200	65
90	420	520	240	80
100	455	580	250	85
104	470	600	260	87
109	495	620	270	90

Table 4.0: Turbopump generated synchronous frequency (hz) SSME turbomachinery.

Table 4.1 is used to identify the bearing generated frequencies for both the pump and turbine end. Note the numbers are multiplied by the synchronous frequency for the respective pump to obtain the frequency window. "SUDO" uses data for the HPFTP 3 times speed synchronous speed plus or minus a specified number to create unique windows for the pseudo 3n and super pseudo 3n event (see figure 4.4). Subproblems "SYNPWR", "FEDMLT", "BRNG" and "SUDO" use the tabulated data to infer the turbopump operation.

Both the interactive and batch module use an analysis procedure. First a window is described using information in the above tables. This window is compared to the sinusoid in question. If the sinusoid falls within the window range then ADDAMX can hypothesize a possible frequency generated source as indicated by the respective known frequency window range. Verification of the hypothesis is done by comparing data collected from the surrounding accelerometers or other criteria to the hypothesis. A voting scheme is used in the verification step. Finally the results are printed to the screen or on to a hardcopy plot. Figure 4.5 displays a flow chart of the procedure.

	* LOX *				* FUEL *			
	HIGH PRESSURE		LOW PRESSURE		HIGH PRESSURE		LOW PRESSURE	
CLASS	TURBINE END	PUMP END	TURBINE END	PUMP END	TURBINE END	PUMP END	TURBINE END	PUMP END
BPFI	7.5(fsync)	7.5	8.0	7.6	8.0	8.0	8.0	7.6
BPFO	5.5	5.5	6.1	5.4	6.0	6.0	6.1	5.4
BSF	3.1	2.9	3.5	2.8	3.3	3.3	3.5	2.8
FTF	.42	.42	.43	.42	.43	.43	.43	.42

BPFI: Ball Pass Frequency Inner   BPFO: Ball Pass Frequency Outer
BSF : Ball Spin Frequency   FTF : Fundamental Train Frequency

Table 4.1: Bearing generated frequencies SSME turbomachinery

```
      super       pseudo       3n       pseudo      super
    |--------|/////////////|-------|/////////////|--------|
3n-520   3n-220         3n-20   3n+10        3n+210    3n+510
```

Figure 4.4: Pseudo and Super Pseudo 3n window range.

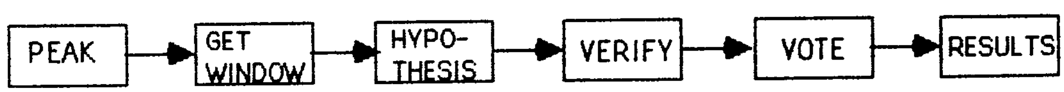

Figure 4.5: Analysis procedure.

5.0 CONCLUSION

The expert system ADDAMX identifies selected sinusoid frequencies from Spectral Data graphs as speed frequencies and harmonics from each respective turbopump, frequency feed through from one turbopump to another, frequencies generated by the turbopump bearings, pseudo and super pseudo 3N for the phase 2 HPFTP and finally electrical noise. ADDAMX does the analysis in an interactive or batch mode and the results can be displayed on the screen or hardcopy.

ADDAMX is in its infancy; however, it is helping to share the knowledge from the expert and associates with other groups. It is anticipated that the knowledge base will continue to grow to handle additional types of anomalies and increase in its capability through an organized effort from a dedicated department group.

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