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velopment Of An Off-Line Expert System For Condition Monitoring Of An Aircraft gine

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BSTRACT

e aim of the current work is to develop an off-line system for the condition monitoring of an aircraft engine, ., AI20D. Currently, the engine comes to the test bed for repair if the overall vibration level at certain points ecomes above a certain threshold, or at a predetermined time between overhauls (TBO). It is now proposed at the vibration signature be converted into the frequency domain and use in an expert system to try and cate any fault on the basis of the predominant frequencies, location of the predominant frequencies, erating conditions and other related parameters. This requires experimental data from the engine test bed r a long period of time. This data is not yet available. Currently, data regarding the bearings, gears, compressors etc. of the different rotating parts of the engine has been collected. The safe limits for vibration evels in the frequency domain will be established after the data has been collected for a sufficient length of me and compiled. Steps are on for collecting such data. Meanwhile, an interactive off line expert system has een developed based on the predominant frequencies present and their directions etc.

eywords: Condition Monitoring, Off line Expert Systems, Rotor Dynamics, Fourier Transforms

. INTRODUCTION

Rotor dynamics plays an important role in the design as well as operation of modern rotors in a ealthy manner. The rotating machines are often very expensive, as in electric utilities or aircraft engines, here the availability of the machine is a prime economic factor. The failure of a machine may cause loss of ndreds of millions of dollars besides being catastrophic in nature, e.g., the Narora atomic power plant ilure on 31st March 1993 in India [1,2]. Continuous condition monitoring and analysis of the behavior of the achine is therefore essential.

Condition monitoring of rotating parts based on vibration signals and its subsequent analysis has now become a standard practice. Typically the vibration signal from the bearings is recorded. This vibration gnature contains valuable information about the health of the machine. The vibration levels at different equencies give important indicators towards the faults that could be causing the vibration. Therefore as the bration level in each frequency content crosses a particular level it can be considered as an indicator of a pecific fault. This approach has been tried for different kinds of rotating and reciprocating machinery.

Basic principles of rotor dynamics and the response to different kinds of excitation are well cumented, e.g., Rao [3]. Practical applications of rotor dynamic behavior is aptly presented by Wowk [4]. easurement of rotor vibrations of various types of machines over a long period of time have been used by Sohre[5] to develop general guidelines and rules for maintenance of rotating equipment. With the dvancement of microprocessors and PC based systems, expert systems are developed, e.g., [6]. Data ases such as those of Sohre [5] are now built as expert systems to aid the maintenance managers in eventing any impending rotor failures or in making a good and speedy diagnosis of failures that have taken place. A general Off-line expert system based on Sohre's rules was developed by Rao et al [7], which [illegible] later demonstrated as an On-line system [8].

With respect to aircraft engines, the current practice of condition monitoring comprises of recording overall vibration levels at a few critical locations of the rotor during level flight. These levels are transferred to the base computer (in some cases via a satellite) to obtain the engine trend over the immediate past as well as the long term trend. Rules are developed to analyze the trend and decide upon the maintenance attendance procedure as and when called for. While the trend monitoring has improved the engine availability considerably, it is still not a continuous condition monitoring and simultaneous analysis. Development of an expert system and on-board monitoring will go a long way in aiding the pilots for quick and correct decision making in case of an engine failure or an impending failure.

The aim of the current work is to develop an off-line system for the condition monitoring of an aircraft engine, viz., AI20D. Currently this engine is maintained using conventional methods. The engine comes to the test bed for repair if the overall vibration level at certain points becomes above a certain threshold, or at a predetermined time between overhauls (TBO). It is now proposed that the vibration signature be converted into the frequency domain and use an expert system to try and locate any fault on the basis of the predominant frequencies, location of the predominant frequencies, operating conditions and other related parameters. This requires experimental data from the engine test bed for a long period of time. This data is not yet available. Currently, data regarding the bearings, gears, compressors etc. of the different rotating parts of the engine is collected. The safe limits for vibration levels in the frequency domain will be established after the data has been collected for a sufficient length of time and compiled. Steps are on for collecting such data. Meanwhile, an expert system to infer the fault has been developed through an interactive medium (off-line) based on the predominant frequencies present, their directions etc.

2. BRIEF DESCRIPTION OF AIRCRAFT ENGINE

The AI-20D engine is a high altitude turbo prop aircraft engine which operates with variable speed propeller rotors in anti-clockwise direction viewed from rear. It comprises of a planetary reduction gear, a front casing, an axial flow ten stage compressor, an annular combustion chamber, an axial flow three stage reaction turbine and a fixed area exhaust nozzle. The compressor and the turbine rotors are inter-coupled through splines and rotate in two roller bearings (B9 and B10) and one ball bearing (B8). Fig. 1 gives a line diagram of this engine. The auxiliary gear drive is as shown in Fig. 2.

3. MONITORING OF THE ENGINE

Presently the engine is monitored by collecting vibration signals from three different locations in the engine. If the peak to peak vibration crosses a certain limit, the engine is sent for repair, otherwise the engine comes for overhaul at predetermined intervals of flying time. In this method if some particular component is faulty, it might go undetected as its contribution to the amplitude-time signal might be insignificant.

In order to correlate the predominant frequency of the vibration signal with a fault, engine data is [illegible] collected and the possible faults have been related with the operating speed. For the compressor and the turbines the number of blades in each stage multiplied with the operating speed gives the blade passing frequencies. The vane passing frequencies have been obtained by multiplying the number of fixed blades by the running speed. These frequencies are tabulated in Tables 1 and 2.

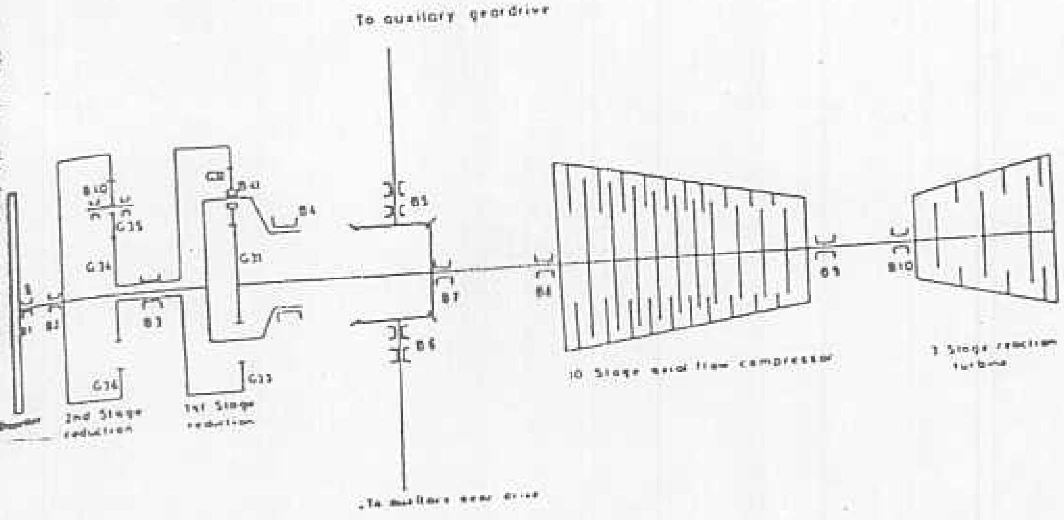

figure 1. Line Diagram of the AI-20D engine

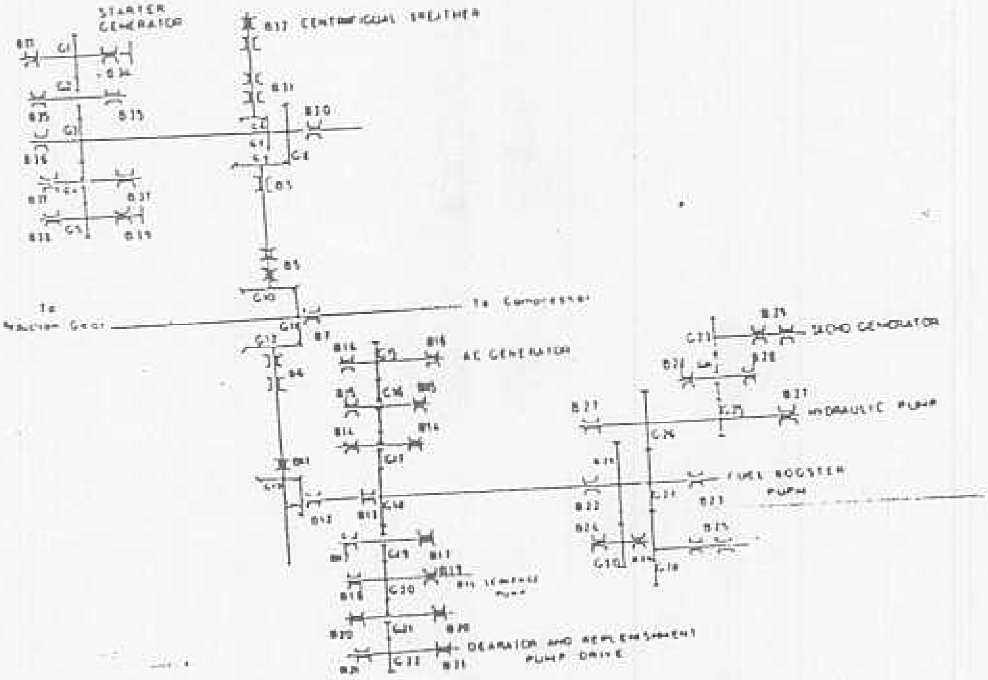

Figure 2: Auxiliary Gear Drive

Rotor No.	No of Blades	Stator No.	No of Blades	Blade passing frequency*	Vane passing Frequency*
1	25	1	34	25	34
2	31	2	40	31	40
3	35	3	44	35	44
4	45	4	62	45	62
....					

* in terms of ERF

TABLE 1: Compressor data (The data is incomplete, as there are a total of 10 rotors)

Rotor No	No of Blades	Stator No	No of Blades	Blade passing Frequency*	Vane passing Frequency*
1	106	1	46	106	46
2	86	2	56	86	50
3	82	3	54	82	54

* in terms of ERF

TABLE 2 Turbine data

Similarly gear tooth mesh frequencies have been computed These give information about meshing defects such as improper backlash, eccentricity, loading etc Gear tooth defects have been correlated with the gear speeds Impacts generated by defective gear teeth at the time of meshing excite frequencies present in the gear system and these frequencies are modulated by the impact rate

As shown in Fig 2, there are a total of thirty six gears in the system A partial extract of the data on gears and the corresponding tooth meshing frequencies is given in Table 3

Gear No.	No of Teeth	Tooth Meshing Frequency*
1	29	0 539
2	38	0 4115
3	34	0 460
4	38	0 4115

* in terms of RPS

TABLE 3: Gear Data (The data is incomplete as there are a total of 36 gears)

There are a very large number of ball and roller bearings In case of faults in either the inner race outer race or the balls/rollers, the predominant frequencies are the corresponding impact rates These have been calculated and vibrations at these frequencies have been correlated with the corresponding faults Table 4 gives a partial extract of the bearing data and the expected damage frequencies calculated th Table 5 gives a partial list of the correlations inferred between the predominant frequencies of vibration and the expected faults

Bearing No	Pitch Dia (mm)	Ball / Roller Dia (mm)	No of Balls or rollers	Contact angle (in °s)	$^{*}f_1$	$^{*}f_2$	$^{*}f_3$
1	183	14.55	24	0	0.916	1.127	1.088
2	180	16.7	14	26	0.558	0.659	0.993
3	120	8.3	14	12	1.58	1.81	3.48
4	180	6.9	26	12	1.088	1.173	2.266

$^{*}f_1, f_2, f_3$ are in terms of ERF

TABLE 4: Bearing Data (the data is incomplete as there are a total of 41 bearings)

Predominant Frequency Present *	Diagnosis
0.558	Outer Race of Bearing No 2 is damaged
0.659	Inner race of Bearing No 2 is damaged
0.916	Outer Race of Bearing No 1 is damaged
0.993	Balls of Bearing No 2 are damaged

* in terms of ERF

TABLE 5: Partial Chart for Bearing Monitoring

4. EXPERT SYSTEM FOR AIRCRAFT ENGINE MAINTENANCE

The aim of the condition monitoring expert system is to analyze the vibration signal and reason about the health of the engine. The vibration signal will be converted into the frequency domain through an FFT program. As the vibration level at certain frequencies becomes higher than a predefined level, a fault can be sensed. The expert system is then expected to find out the likely fault.

This process consists of the following steps

i Getting the vibration signal.
ii Converting it to an amplitude versus frequency signal using FFT
iii Finding out the frequencies at which the vibration levels are critical
iv Running the expert system to find out the fault

Of these, the third stage requires the safe vibration limits at the different frequencies to be decided. This in turn requires the vibration signals to be recorded over a period of time and safe vibration limits be decided on that basis. Since the vibration signals are not being recorded and converted to the frequency domain as yet, it has not been possible to fix these limits. therefore, while this is part of the ongoing work, the current work being reported here concentrates on the fourth phase. When the other data is available, it can easily be incorporated in the expert system developed.

The expert system developed incorporates conditions and symptoms of probable faults the engine can have, likely locations and directions of maximum vibrations for the occurrence of these faults and the effect of the operating conditions. Some of the major faults likely in the AI-20D engine along with the

frequency of the dominant vibrations under the faulty conditions and the direction of the lik
tabulated in Table 6.

Nature of fault	Frequency of dominant vibration	Direction
Rotating Member out of balance	1 * rpm	Radial
Misalignment and Bent shaft	usually 1 * rpm, often 2 * rpm and sometimes 3 * rpm	radial and axial
Damaged rolling element bearing	impact rates for individual bearing components.	radial and axial
damaged or worn gear	tooth meshing frequencies (shaft rpm * no of teeth)	radial and axial
increased turbulence	blade passing and vane passing frequencies	radial and axial
mechanical looseness	2 * rpm	radial

TABLE 6: Some major faults and the expected predominant frequency in theses conditions

Data of the faults and the corresponding frequencies of the predominant vibration
compiled. For the time being, data compiled by Sohre [4] is taken as the basis and suitably modified
AI20D engine. The faults as mentioned in Table 6 and the expected frequencies of vibrations as desc
Tables 3 to 5 are incorporated. However, the percentages indicated in Table 6 have been taken
Tables 7 gives the expected predominant frequency and its likelihood in the final signal for some of
There are a total of twenty seven faults which have been identified. [9] gives the complete table of
faults. Similarly tables have also been compiled for the direction and the location of the pred
amplitudes, for the amplitude response to speed variations, for changes in operating conditions
effects of oil temperature and pressure for each of theses faults. All these tables along with complete
Tables 1, 3, 4, 5 and 7 are available in [9]

Cause of Vibration	Predominant Frequency (in terms of ERF)								
	0-40% of rf	40-50% of rf	50-100% of rf	1 * rf	2 * rf	higher multiples	0.5 rf	lower multiples	odd frequency
Unbalance				90	5	5			
Permanent Bow				90	5	5			
Casing Distortion		5	5	80	5	5			
Seal Rub	10	10	10	30	10	10		10	10
Insufficient tightening in rotor spline coupling			10	80					30

TABLE 7: Partial Chart for Vibration analysis of AI20D engine

The expert system developed is an off-line rule-based expert system in which the user is expected swer a set of questions regarding the different symptoms seen. The questions are put to the user in a f consultation frames in which the user can answer. However, he can skip any particular consultation and go to the next one if he does not have information to answer questions in that frame. The user gates through each consultation frame by moving the cursor and gives his responses in YES / NO. The gram thus collects his answers to all the questions and then computes probabilities of occurrence of all faults. This is done on the basis of the figures given in Table 7. It then gives a list of possible faults in creasing order of probabilities.

program has been developed on a PC486 machine running under MS DOS / WINDOWS environment expert system has been developed using the C++ language.

CASE STUDIES

In order to test the system the expert system was run and given a set of faults. Ideally the faults ould be generated from an actual vibration signal. However, for the time being the faults were given nually, as a set of answers to the different questions asked during the consultation process. The faults ut and the results obtained are as shown in Figs. 3 and 4.

hat frequencies are predominant:	
0-40% of RF	
40-50% of RF	
1 x RF	Y
2 x RF	Y
Higher Multiples of RF	Y
1/2 x RF	
1/4 x RF	
Lower Multiples of RF	
Odd Frequencies	
hether Following frequencies are present:	N
Tooth Meshing Frequencies of all the Gears	
All blade passing and vane passing frequencies of compressor	
All Blade passing and vane passing frequencies of turbine	
Damaged frequencies of all the Bearings Direction of the dominant Amplitude	
Horizontal	Y
Vertical	
al Locations of the Predominant Amplitude	
Shaft	Y
Bearing	Y
Casing	
Coupling	
pe of Amplitude Response to Speed variations (coming up)	
Remains Same	
Increases	Y
Decreases	
has peak value	
Comes up suddenly	
Drops out suddenly	
pe of Amplitude Response to Speed variations (slowing up)	
Remains Same	
Increases	

Decreases	Y
Has peak value	
comes up suddenly	
Drops out suddenly	
Effect of Operating Conditions (Comes or Comes out at)	
No Effect	Y
Full Load in	
Full Load out	
No Load in	
No load out	
Part Load in	
Part load out	
Start up only Effect of Increasing Oil Pressure: The response	
is better	Y
is worse	
Effect of decreasing Oil Pressure: The response	
is better	
is worse	Y
Effect of Increasing Oil Temperature: The response	
is better	
is worse	Y
Effect of decreasing Oil Temperature The response	
is better	Y
is worse	

Figure 3: A set of responses given in the different consultation frames.

Name of the Fault	Probability
Unbalance	100%
Permanent Bow or lost rotor part	100%
Overhang critical	6.1%
Critical Speed	6.1%
Rotor and Bearing System Critical	4%
Rotor rub	3.2%

Figure 4: A set of expected faults and their probabilities for the input of Fig. 3.

The faults as reported by the program are reasonable as they would give the faults that have been fed as being present. For instance, the fault reported is unbalance or a permanent bow in Fig. 4. This is li to give rise to vibrations at running frequencies or at higher multiples, the direction of the amplitude can ei be horizontal or vertical, the amplitude response would be expected to go up with speed and so on. Si these match with the faults input, the expert system seems to run correctly. While this gives some indica on how the system is working, the actual performance of the system can only be tested on the basis of ac vibration signals from the test bed.

6. DISCUSSIONS AND FUTURE WORK

The work reported here is part of an ongoing project. The system developed is very preliminary needs to be substantiated by a lot of data to be collected over a period of time. Specifically the safe lim vibration at different frequencies need to be fixed and the probabilities of the different symptoms need collected.

The expert system developed is an off-line one and should finally be made on-line such th vibration signals from the test bed can directly be analyzed and a set of possible faults be reported ther n then be implemented on-board of the aircraft. Also the expert system developed gives a list of faults decreasing order of possibility of each fault. However, sometime multiple faults might be present aneously. Techniques can be tried where best possible combination of faults can be reported by the m.

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