An experimental study of the effects of engine torque variation on the power spectrum of a healthy and a cracked helicopter transmission

by
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Abstract: The effects of engine torque variations on the power spectrum of a UH-60A Blackhawk helicopter transmission are examined using data from tests on the ground and on a test bed. The measurements were performed on healthy and faulty transmissions for a particular serious type of fault namely a cracked planetary gear plate. The analysis also includes some preliminary experimental data from a seeded crack that was introduced to investigate crack growth rates, fault diagnosis and prognosis. For the simplification of the mathematics a novel straightforward technique for vibration mode analysis is introduced that can considerably simplify the corresponding codes for feature generation, diagnosis and prognosis based on the FFT transform. The numerical results strongly indicate that as the crack develops in size its effects on the emitted power spectrum to tend shift between damping to amplifying certain vibration modes, a phenomenon that complicates the feature extraction procedure that needs to be adjusted to include also the damping effects. These damping effects are closely related to the internal grinding of the new metal surfaces created by the crack progress.

Key Words: Fault Diagnostics, Crack Detection, Feature Extraction, Planetary Helicopter Transmission, Planet Carrier Plate.

1. Introduction

The problem in question was initially diagnosed when during routine engine checks caused by a low oil pressure indication; cracks were then discovered on two carrier plates of the transmission of an US Army UH-60A Blackhawk helicopter.

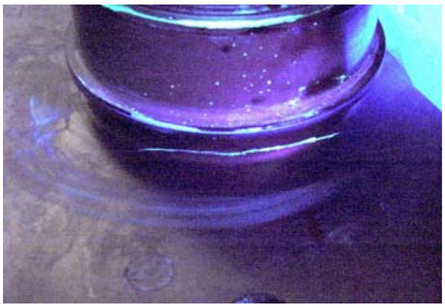

Fig. 1. Crack Length 8 cm approx.

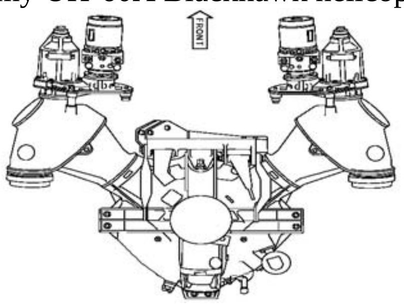

Fig. 2. Sensor Location

Illustrations Courtesy of Keller, Johnathan, Grabill, Paul, "Vibration Monitoring of a UH-60A Main Transmission Planetary Carrier Fault."

The cracked transmission was tested and data were collected with a measuring frequency of 100 kHz, using an array of accelerometers. The whole test lasted for 180s that correspond roughly to 720 revolutions of the plate for each engine torque setting. The nature of the crack was analyzed by Sahrmann [1] who concluded it was a low cycle fatigue. Technical details of the sensors used and the vibration monitoring process were given by Keller [2] and will not be repeated here. The location of the four vibration sensors in these experiments is outlined in Fig. 2. This type of problem in not restricted to helicopter planetary transmissions, but it appears also in other engines, as for example in excavators and bulldozers. In the case of the plate in figure 3 from an excavator all five posts had similar cracks at various degrees of advanced progress. Fig.3 illustrates the most advanced crack in post#1. This plate was made of St50, a relatively less brittle material than the high tech titanium plate in the helicopter, which explains the coexistence of five advanced cracks.

Fig. 3. Carrier Plate with five cracked posts.

Fig. 4. Carrier plate #1 post crack

In the case of the helicopter carrier plate tests were performed on the cracked and several healthy transmissions on helicopters on the ground as well as at the Helicopter Transmission Testing Facility at Patuxant MD. Detailed experimental measurements were also carried out on a rotor with an artificially produced crack.

1. Physical Considerations

For most engineers the present of a fault naturally creates the impression that the net result will be an increase of vibration energy which will be distributed to specific modes amplified by the mechanism of crack propagation. On the basis of this “principle” a crack is considered as a mechanism which increases the degrees of freedom of a system and therefore leads to an increase of vibration energy. This view may be fairly accurate when the crack is sufficiently developed and threatens the integrity of the part. However, when the crack is generally small or contained in the interior of the part, the major effects on the vibration energy distribution on the various modes may be due the dissipative nature of the crack. In such cases dissipation is caused by the friction between the two metallic surfaces of a crack. Thus for the earliest possible detection of a crack, one should concentrate his attention to the dissipative nature of the crack and develop generalized features that take into account also these effects.

2. Mathematical Background

In machine fault diagnosis the normal approach is to compare at specific instances the incoming real time data from a set of sensors with a preexisting data from the same sensors when the machine was in good operating condition. This relatively straightforward procedure is not as simple as it seems, because there are various phenomena that tend to confuse the issue, as for example, the normal wear that has increased the clearances between healthy moving parts. Another serious factor is the level of the engine torque, or possibly the existence of transient conditions of machine operation in any normal flight. In the present case the type of sensors used for fault diagnosis were accelerometers, so it is natural to compare the FFT power spectrum and try to identify specific modes which are either amplified or attenuated because of the presence of the existing fault. For this reason the present approach treats both cases with equal care. The basic novel idea when we compare two FFT power spectrums is to define an index vector that has 1 for each frequency where the faulty signal has a larger mode than the healthy signal and -1 in any other case. If $m_h(f)$,

$m_f(f)$ are the modes corresponding to any frequency f of the "healthy" and the "faulty" signals, then the corresponding algorithm for the index vector is simply:

$$\mathrm{Ind}(f)=+1 \text{ if } m_h(f)<m_f(f), \text{ and } \mathrm{Ind}(f)=-1 \text{ if } m_h(f)>m_f(f)$$

The vector Ind has several interesting properties:

1. By adding the corresponding vectors of two signals and divide by two we obtain the corresponding index vector which contains only the frequencies that are amplified and attenuated in both signals, since this is essentially a logical AND operation. This procedure could be applied for n signals in which case the resulting vector will have to be divided by n. In such a case we obtain a vector function s(f) that has as elements the "probabilities" that in n signals a certain frequency has modes consistent with the general principle of mode amplification or attenuation in the case of a fault.
2. By subtracting the corresponding vectors of two signals we obtain the corresponding vector that contains the "noise", i.e. the vector that contains all the modes that are present in the two signals with opposite signs.
3. By multiplying the corresponding vectors of two signals we obtain a vector that has 1 in all the frequencies where in both signals consistent with the general principle of mode amplification or attenuation in the case of a fault and -1 when one of the two signals was inconsistent.

3. Numerical results

a. Ground tests. In this case six sets of measurements were performed on the test bed using 20%, 30%, 50%, 70%, 90%, 100% for the healthy carrier plate and six sets for the cracked. In both cases the signals were divided into 72 segments corresponding to 10 carrier plate rotations.

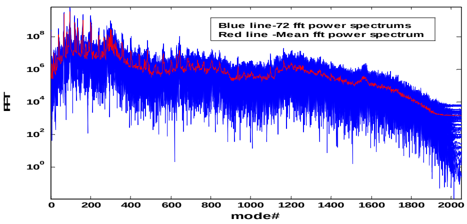

Fig. 5 FFT power spectrum band and mean
Healthy plate, torque 100%, PortRing sensor

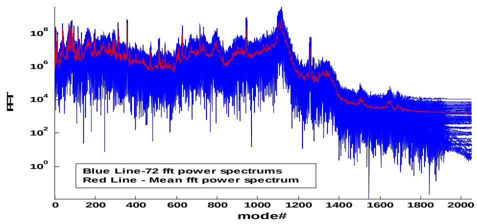

Fig. 6 FFT power spectrum band and mean
Healthy plate, torque 100%, Input2 sensor

In Figs. 5, 6, the FFT bands corresponding to 100% engine torques and the mean FFT are illustrated for the healthy plate using the PortRing and Input2 signals. We may note that even without the presence of the helicopter rotor there are considerable variations of the signal FFT within the band which indicates a "noisy" engine operation. Similarly structured FFT's were obtained in the case of the cracked plate for the corresponding sensors and will not be presented here for brevity. These results indicate there are considerable differences between the PortRing and the Input2 signals. In fact, the signals from the sensors PortRing and StbdRing located at the vicinity of the transmission were similar, as well as the signals from the remotely located sensors Input1, Input2. Since in most cases many sensors are used for diagnostic purposes, the question which signal is the most appropriate for diagnosis naturally arises. This choice can by simplified by the use of the index vector and the corresponding Probability of Success function s(f) defined by the formula:

$$s(f) = \Big(\sum_{1}^{m} \mathrm{Ind}(f)\Big)/m$$

Where m is the number of FFT power spectrums corresponding to the m consecutive segments of the signal, and f the corresponding mode. In our case the choice was m=72. The corresponding s(f) for the PortRing sensor for the cracked plate using as references the mean FFT's for these torques are illustrated in Fig. 7.

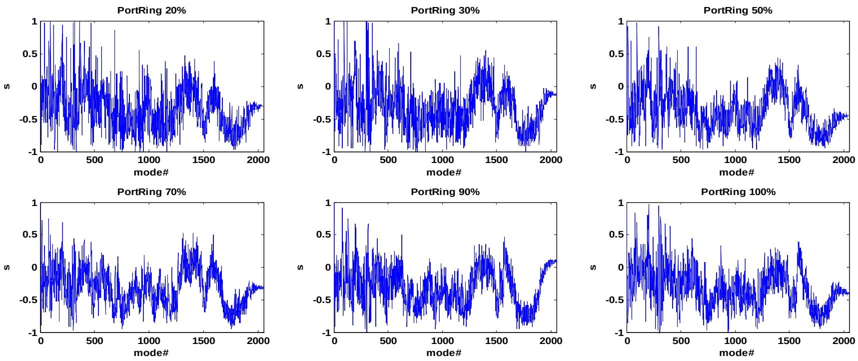

Fig. 7. The Probability of Success function s(f) for the PortRing signal

Close examination of fig. 7 reveals that there are no modes that are consistent with any maximum noise principle for all torques. This means that there is no feature which is a hundred percent successful using a single mode. However, one can obviously create features that are linear combinations of specific modes that can successfully diagnose the presence of the crack. In such a linear combination feature modes f with s(f)>0 should be used with a positive sign, whereas modes f with s(f)<0 with negative. Clearly there is an infinite number of such features. By observing the general shape of these curves that tends to lie below the value of s(f)=0 it is clear that the presence of the crack tends to consistently attenuate modes rather than amplify them! The physical explanation of this phenomenon is the existence of friction between the crack surfaces. When a crack progresses by dS occupying a surface S+dS, initially the surface increment dS is rough as the crack surface follows the boundary surfaces of the microcrystal structures. As the crack normally advances in finite steps, initially there is considerable grinding between the two crack surfaces due to their microscopic relative motion. This grinding will affect some modes more than others by dissipating their energy, i.e. by damping them. The damping effects caused by the crack are clearly beyond the analyzing capacity of simple models related to tooth cracks [3,4]. Let's now try to estimate the relative performance of the four sensor signals. Since, the ideal case would be a s(f) that is constant either 1, or -1 for all modes, a useful coefficient can be defined by the norm of the s(f) vector function, namely:

$$S_{fac} = \sqrt{(s \bullet s')} \,/\, m$$

Where m is the number of signal segments (m=72).

"Probability" Norm S_{fac}				
	Sensor			
Torque	PortRing	Stbdring	Input1	Input2
20%	0.010562	0.010411	0.011901	0.011771
30%	0.010017	0.010263	0.010366	0.012118
50%	0.010476	0.010261	0.010232	0.0133
70%	0.0093262	0.0092009	0.009673	0.012608
90%	0.0093757	0.0089248	0.01	0.014008
100%	0.0096125	0.0090075	0.0095558	0.012263
Sum	0.059369	0.058068	0.061728	0.076068

For the existing four signals the following table has been compiled for each load. The results indicate that the Input2 signal has the most consistent record. Since Input1, Input2 sensors are located further away from the engine transmission this is a rather surprising result for anyone who thinks that a carrier plate crack development is a phenomenon that has to be monitored by sensors in the vicinity of the crack. Therefore, to accurately assess the effects of the fault, one has to keep a distance from the oscillating parts that tend to confuse the issue. The final question that needs to be addressed is what kind of feature someone would need to create to diagnose and prognose such phenomena. As we mentioned before, a possible solution is to create a linear combination of all the modes that have s=1 with a positive sign and all the modes that have s=-1 with a negative sign. Indicative results are illustrated in fig. 8 for all sensors.

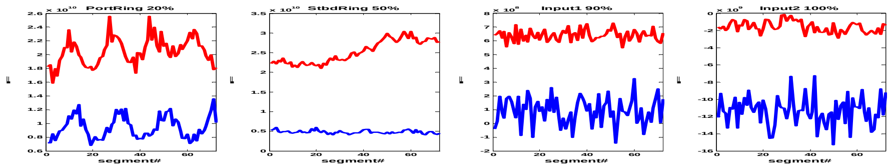

Fig. 8. Diagnosis for all available signals (Red line-Cracked plate, Blue line-Healthy plate)

b. Helicopter tests: In this case only the low torques of 20% and 30% were used for both the crack and healthy plates for safety reasons. For the tests shorter time intervals were used for data collection, as well as lower sampling frequencies (48kHz).

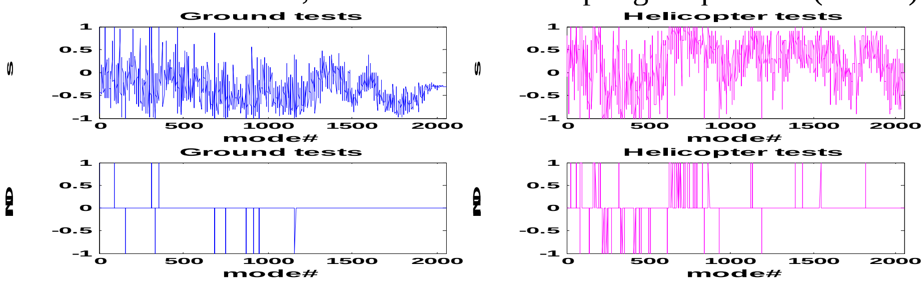

Fig. 9. Probability of Success functions s(f) and index vectors comparison for the ground and helicopter tests in the case of the 20% torque for the PortRing signal.

It is interesting to see how the signal of the ground tests compare to the one on the helicopter. This is illustrated in fig. 9. The most obvious effect is that the rotor assembly excites a large number of modes in the entire spectrum which can be used for the development of features. A comparison of the the corresponding features for the PortRing sensor at 20% torque using all modes f with s(f)=1, or s(f)=-1 are illustrated in fig. 10.

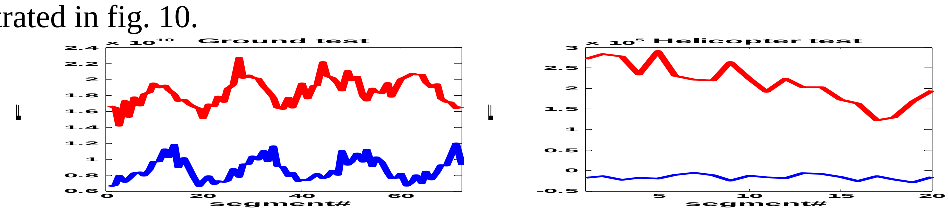

Fig. 10. Feature performance comparison for the ground and the helicopter tests

c. Seeded fault ground tests: During these series of tests an artificial crack has been introduced on the helicopter transmission planet gear carrier plate and the engine was loaded with a sequence of specific torque loads namely 20%, 40%, 100%, 120% simulating a ground to air to ground (GAG) flight.

GAG	0	36	100	230	400	550
Crack length	1.344”	2.0”	2.5”	3.0”	3.5”	4.1”

The proposed approach allows us to examine the development of the crack in terms of the changes of the index vector.

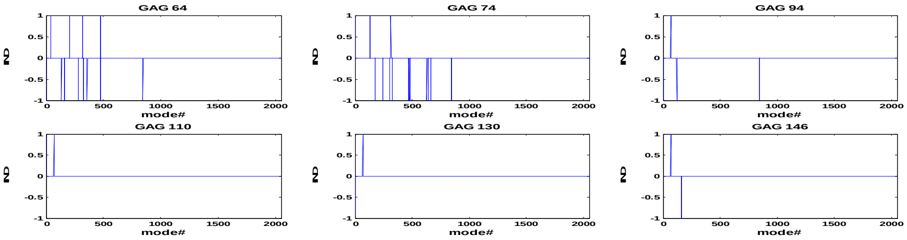

Fig. 11. The change of the Index vector with respect to GAG 55 as the crack progresses (PortRing, 20% torque)

The considerable variation of the Index vector for the GAG 64-146 cycles is a strong indication that a crack is present and rapidly progressing.

Conclusions

a. Test bed data:

1. All four available sensor signals contain information that could be used for feature extraction (as it should) using the proposed method.
2. There is an infinite choice of features that can be assembled by a linear combination of modes that are amplified by the presence of the crack with a positive sign and modes that are attenuated by the crack with a negative sign.
3. The crack is a mechanism that amplifies and attenuates specific modes (obviously). Both types of modes should be used for feature extraction for maximum distinction of the fault.

b. Helicopter data:

1. The Index vector is useful to determine the presence of a crack on the carrier plate.
2. In view of the considerable differences of the vibration signal between the test bed data and the helicopter data, a specialized feature has to be used in each case.

c. Seeded crack data:

1. The existence of a crack on the carrier plate may be diagnosed by the rapid changes of the index vector.

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