Vibration Health Monitoring of Helicopter Transmission Systems at Westland Helicopter Ltd.

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Abstract

Korea Aerospace Research Institute (KARI) have gained experience with Helicopter Vibration Health Monitoring (VHM) System technology with the help of UK GKN-WHL. GKN-WHL have had many years of experience with the research and development of vibration analysis techniques to improve the health monitoring of helicopter transmissions. This activity was targeted at transmission rig testing at first, but the techniques have been progressively developed where they are now used as a part of integrated Health and Usage Monitoring (HUM) systems on many types of in-service and new helicopters.

The technique development process has been considerably aided by an ever expanding database of transmission monitoring experience from both the rig testing and aircraft operations. This experience covers a wide range of failure types from naturally occurring faults to crack propagation studies and covering a wide range of transmission configurations. Primarily based on accelerometer signals GKN-WHL's vibration analysis methods have also been applied to a variety of other sensor types. The transition from an experimental environment to operational VHM systems has been a lengthy process, there being a need to demonstrate technique reliability as well as effectiveness to both regulatory (Airworthiness Authority) and commercial organizations. Another important feature of this process has been the development of close relationships with a number of VHM system hardware and software suppliers.

Such an experienced GKN-WHL provides various raw vibration data which was acquired from transmission ground test rig and allow KARI to develop it's own analysis program. KARI made a program and then analyzed the data to comapre with the results of GKN-WHL. The KARI's results both time domain signals and statistical values show comparable to GKN's.

Key Word : VHM, Vibration Analysis, Transmission Ground Test Rig

Introduction

It has been known for a long time that the vibration produced by a gearbox can be analysed to yield information about the condition of its components, including internal gears, bearings and

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shafts, and the casing. Less well publicised has been the difficulty of segregating and quantifying that vibration information which is specifically related to a type and severity of component damage.

GKN-WHL's vibration health monitoring (VHM) techniques are now used in an executive capacity to identify defective transmission components in both rig testing and on the aircraft. This paper illustrates the basic transmission vibration monitoring techniques that have been developed by GKN-WHL but newly realized by KARI and the GKN's manner in which the technology has been applied to in-service Helicopters.

I. Early Vibration Monitoring Studies at GKN-WHL

By the late 1960's GKN-WHL were routinely conducting narrow band frequency analysis of gearbox vibration as a means of identifying component distress in gearbox fatigue and endurance testing. The confidence to terminate testing and prompt a strip examination was founded on experiences with earlier test cases and vibration analysis of deliberately seeded faults in gears and bearings.

Through the 1970's the quality of the frequency analysis equipment improved but despite efforts to automate or 'simplify' the analysis process, the success of the procedure remained heavily dependent upon the expertise of the analyst. Such techniques as plotting the side-band behavior about the gear meshing frequency and its harmonics produced reliable trend information for certain categories of gear and shaft faults but the analysis and plotting equipment remained laboratory based, using tape recordings of accelerometer signals gathered at the test site. Time domain portrayals of gearbox vibration using a 'raster' technique provided a visual means of enhancing, and locating to a shaft, the source of a gear defect.

In the late 1970's, proprietary frequency analysis equipment was replaced by a digital computer based system. This immediately introduced a step change in processing flexibility and in particular provided an opportunity to exploit the long established synchronous time averaging (signal averaging) process.

1.1 The GKN-WHL Transmission Vibration Database

As mentioned above, GKN-WHL regard their continually expanding data base of analogue transmission vibration recordings as an indispensable archive of information for the development and evaluation of techniques. The data base has been accumulating for over 30 years and includes comprehensive coverage of nearly all of the gearbox development testing at GKN-WHL over that period. From the early 1980's there has been an expanding data base of analogue vibration recordings, and digitally processed data, from the transmissions of in-service civil and military helicopters. A large portion of the data comes from helicopters not manufactured by GKN-WHL, but which incorporate GKN-WHL vibration health monitoring technology.

Initial analogue recordings and pre-processed digital data from the aircraft are of vital importance when fine-tuning algorithms and automatic acquisition windows for sensitivity under conditions of 'normal variability'. They also can present examples of degenerated or corrupted signals that have to be expected and accommodated in 'real-life' monitoring situations. Data-handling routines have been developed to enable health monitoring algorithms and thresholds to be subjected to a group of test cases from the archive with the minimum of human interaction.

II. The Basic Vibration Analysis Process

2.1 Data Acquisition

Transmission vibration is usually monitored by accelerometers mounted at strategic locations on the gearbox casings. A newly developed GKN-WHL helicopter EH101's accelerometer installation for Transmission HUM system and ground test rigs are shown in Fig 1. There are 17 accelerometers on this transmission at locations established after a consideration of the internal geometry of the gearbox, and then optimized to achieve high quality signals from all target components with the minimum number of transducers. Shaft speed reference (azimuth) signals are also required (AZ in Fig 1 (a)). Figure 3 shows an example of a raw transmission vibration signal (from a Lynx intermediate gearbox). This gearbox has 23 tooth input pinion, rotating at 4,308 rpm, and a 27 tooth output gear. The vibration data was acquired at a sample rate of 36,760 Hz and pre-conditioned by a 12 KHz low pass anti-aliasing filter.

Experience has shown that retaining frequency information up to about the 7th harmonic of mesh frequency can assist in obtaining reliable and early diagnosis of impending malfunction of gear mesh. Signal processing theory demands a sample rate of at least twice the highest frequency of interest.

2.2 Data Processing

Signal quality or 'integrity' checks are implemented on the digitised raw vibration signals (Fig 3) and at other stages in the processing network. The network manipulates the signals in different ways depending on the component and the component defect mode being investigated.

For the identification of faults in gears and shafts, the well-known process of signal averaging is employed. The process 'averages out' constituents of the gearbox vibration signal that are not synchronous in rotation to the particular gear shaft being analysed. Information relating to the cyclic behavior of the target shaft, and any gear on that shaft, is not degenerated by the averaging procedure and so can be studied for defect information against a now very low level of background 'noise'. The number of averages is selected after consideration of sensitivity, file size and the stability of operating conditions.

Gear tooth defects are often masked by regular meshing then in the signal average. Therefore an enhanced form of signal average is generated where only vibration components relating to differences in the meshing action from tooth to tooth are retained. A defect upon a single tooth (localized) will typically generate an impulse that increases in amplitude with propagation.

Various health monitoring parameters such as mean, standard deviation, 6th statistical moment and peak to peak are calculated from the distribution of points in the enhanced signal average and/or signal averaging and these parameters are interpreted in combination to identify(i.e, set the threshold) the type and severity of gear tooth ,shaft and bearing distress.

Fatigue cracks in gear shafts and gear webs will invariably change the torsional stiffness of the assembly. This is conveniently detected by utilizing changes in the frequency spectrum of the signal average. Different groupings of shaft rotational orders will respond to different crack geometries and health monitoring parameters have been developed to identify the type and severity of emerging forms of distress. A shaft or gear web crack will typically generate an imbalance that disturbs the regular meshing pattern. Fatigue cracks in the gear teeth themselves generate effects better identified in the time domain as illustrated later.

In the case of bearing fault detection, the vibrational disturbances generated by defects in rolling contact bearings are only loosely repetitive in time (irregularly spaced impulse shapes) and character. Defects on the rotating elements will contact at varying spatial distances and orientations with respect to both the vibration transducer and the applied load, and with a progressive and complex lag as a result of sliding or 'slip' of the rolling elements. A bearing analysis process is used which accepts unstable behavior but emphasizes disturbances in motion by the removal of uninformative constituents of the total vibration signal, including of course the vibration at frequencies associated with the regular meshing action of gear teeth. The nature and severity of any bearing distress is assessed using parameters which describe features of the 'enhanced' vibration signal.

2.3 Signal Average Processing Algorithm

The time domain signal averaging technique has proved to be fundamental to the implementation of an effective transmission vibration monitoring for gears and shafts. Signal averaging provides a means of suppressing vibration sources that are not synchronous with the gear/gear shaft being analysed. A shaft azimuth reference signal is employed to provide accurate partitioning of the raw signal into one shaft revolution length.

The number of points (NP) in each signal averaging block equals,

$$NP = N \times H \times F$$

Then the sampling frequency (sample rate) is

$$f_s = \frac{1}{NP \times \frac{RPM}{60}}$$

where, N : Number of gear tooth
H : Desired number of harmonic (7 from empirical figure)
F : Factor for Nyquist Frequency (more than 2)
RPM : Reference Shaft Rotation Speed.

The signal averages required to represent a pair of meshing gears are as follows(fig 2(a)):

$$\overline{S(NP)}_{input} = \frac{1}{m} \sum_{i=1}^{m} s(i)_{j\,input}$$

$$\overline{S(NP)}_{output} = \frac{1}{m} \sum_{i=1}^{m} s(i)_{j\,output}$$

where, $j =$ 1 to NP
$m =$ [Number of Averages (*typically*, 20 ~ 100)]
$\overline{S(NP)}$: Signal average
$s(i)_j$: Raw measurement signal

Generally, the signal averaging process only is not sufficient to identify and extract health monitoring parameters. An enhanced signal averaging(fig 2(b)) method which performs frequency domain smoothing for each gear meshing harmonic frequency is used for further processing of signal averaging results.

$$\hat{S}(f-f_{M_k}) = \left(\frac{1}{4}\right) \times \left[S\left(f-\left(f_{M_k}-\frac{2f_s}{NP}\right)\right) + S\left(f-\left(f_{M_k}-\frac{f_s}{NP}\right)\right) + S\left(f-\left(f_{M_k}+\frac{f_s}{NP}\right)\right) + S\left(f-\left(f_{M_k}+\frac{2f_s}{NP}\right)\right)\right]$$

where, f_{M_k} : Meshing frequency harmonic terms
$k =$ 1 to 7 harmonics

2.4 Gear Tooth Defect Example

Figure 4 (a) and (b) are examples of signal averages of vibration of the Lynx intermediate gearbox input shaft. Figure 4 (a) represents a gear in normal condition and is the signal average of the raw data shown in Figure 3. Figure 4(b) is the vibration of the same shaft but later in the test when a tooth defect had occurred. In this case, the fault mode was a classical tooth bending fatigue failure, a crack forming in a tooth root and propagating into the gear web. It is not easy to identify the defect in figure 4(b) without further processing.

Figure 5(a) and (b) show enhanced versions of Figure 4 (a) and (b) respectively. By removing the regular meshing effects (by enhanced signal averaging), the defect is now clearly visible.

2.5 Shaft Defect Example

Figure 6 (a) and (b) are examples of signal averages of EH101 Tail take-off shaft vibration. Figure 6 (a) shows the signal average of vibration when the shaft was in normal condition, and figure 6 (b) the same shaft later in the test when it was a suffering from a fatigue crack. The fatigue crack has caused a variation in rotational stiffness and this has resulted in both AM(Amplitude Modulation) and FM(Frequency Modulation) of the vibration signal [2]. This modulation is detected health monitoring parameters operating in both the time and frequency domains.

2.6 Bearing Defect Example

Figure 7 (a) and (b) are examples of raw vibration signal from a Lynx Tail drive shaft hanger bearing. The first example is normal condition. The second is the same bearing but later in the test containing a failure. In the latter case, the bearing was suffering from surface breakdown of its inner race. This is one of the few cases where the defect was clearly visible in the vibration signal without resort to signal enhancement.

2.7 Statistical Assessment of Condition

To convert vibration signals into fault detection descriptors and introduce thresholds we use standard statistical method i.e, health monitoring parameters.

Health monitoring parameters are derived for all signal types. For the gear tooth defect signal averaging in figure 4, the difference between normal and defect parameter is small, but the enhanced signal average in fig 5 shows big difference, as evidenced by the value of M6 in table 1. Similary the peak to peak value of the enhanced signal average also increases significantly. For the gear shaft defect in figure 6, defect parameter peak to peak double in amplitude from the normal condition. For the bearing defect in figure 7, M6 defect signal shows nearly 10 times the impulsive characteristics from the normal condition, even in the raw signal.

III. GKN-WHL's experience of In-service Helicopter HUM System[1]

3.1 Lynx VHM Trial

The UK Army and Navy wished to assess the feasibility of using portable VHM equipment in the military environment. The Westland 30-100 'Vibration Analysis System (VAS)' design was suitably modified and a small batch of prototype VAS units were produced to supply to Squadrons operating Lynx Mk1 and Mk3 helicopters. PC-based ground stations were also supplied to enable further processing of data gathered on VAS to the stage where a 'condition report' was presented to the maintenance engineer. Vibration samples were gathered every 25 flying hours from 8 Army and 8 Navy Lynx, both in ground running and in flight.

Valuable experience was gained by all concerned. Although the excercise was very successful at identifying the only instances of gear distress that occured, the services had varying degrees of success in installing and maintaining their own aircraft instrumentation and there were logistic difficulties in too frequently taking samples with the VAS. The ground station was found convenient and easy to use.

3.2 EH101 HUMS

The EH101 was designed with a fully integrated HUM system with flexibility in the design of the on-board and ground station functions to suit the needs of military and civil customers.

Agusta has responsibility for the design of the transmission system and its health monitoring needs. GKN-WHL are assisting with the development of the VHM system as required, in particular, the definition of advanced algorithms for the RAF Merlin HC Mk3 variant, including those for the transmission, engines and structure.

EH101 is the first Helicopter which required a HUMS at the design phase, having to meet operators' requirements and to satisfy new safety requirements.

IV. The Future

GKN-WHL will continue to expand its knowledge base in the field of transmission VHM. They are currently focusing on the following areas:

1) Respond to the challenge of implementing HUM Systems in new aircraft designs (ex. Generic HUMS and Apache).
2) Further research into the use of Artificial Intelligence techniques in condition assessment. In particular the use of Neural Networks as an alternative to traditional algorithm based diagnostic routines, and data mining as an aid to database management and interrogation.
3) Research further alternative sensor types including Kinematic and other phase based types. Also the use of smart sensor technology.
4) Further optimisation on vibration techniques as applied to helicopter engines and structure.

Conclusions

The vibration health monitoring of helicopter transmissions has evolved at GKN-WHL from an interesting research activity to committed systems on production helicopters.

VHM can identify the actual components of concern within complex assemblies, and also identify failure modes such as fatigue damage which issue little or no debris for detection by other means.

Important benefits from the HUM systems are enhanced safety, prolongment of service life and reduction of long term maintenance cost. Aged aircraft can expect more frequent mechanical failures. An exponential increase of maintenance cost results from mechanical failures proportionally to its years of service. So, a retrofit HUMS for aged Helicopter gives potentially the greatest benefit.

Acknowledgement

The author wish to acknowledge the support given by GKN-WHL Vehicle Dynamics Dept Engineers, their sharing of information and their friendship during work together.

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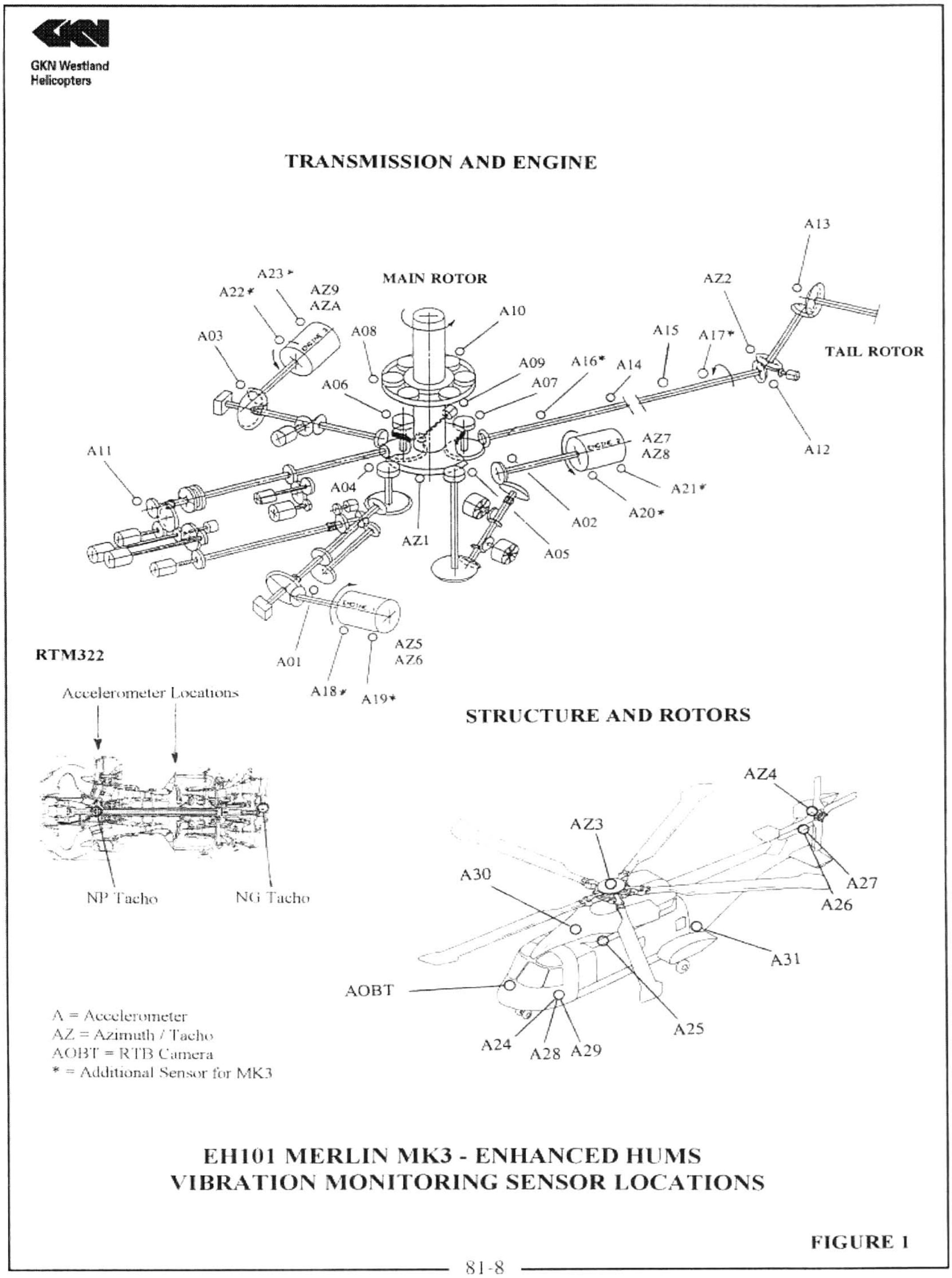


Fig. 1 (a). EH101 MERLIN MK3 - Enhanced HUMS Vibration Monitoring Sensor Locations

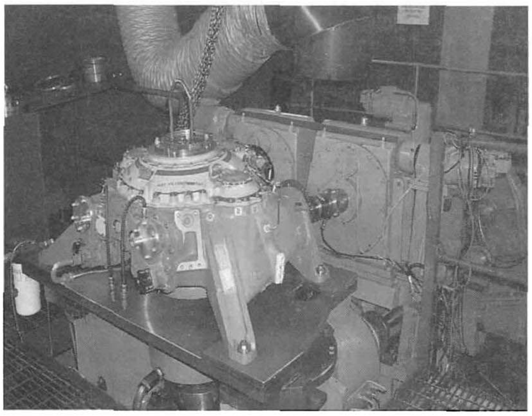


Fig. 1 (b). Lynx main gearbox test rig

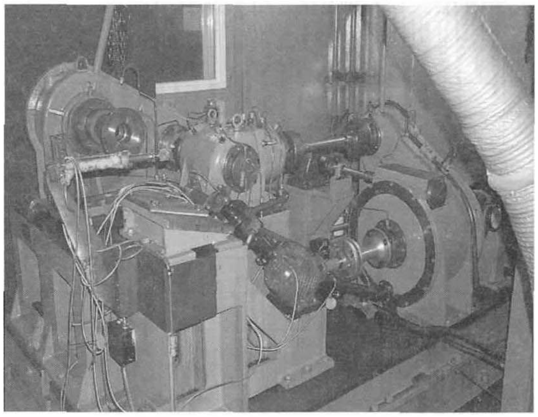


Fig. 1 (c). Lynx intermediate gearbox test rig

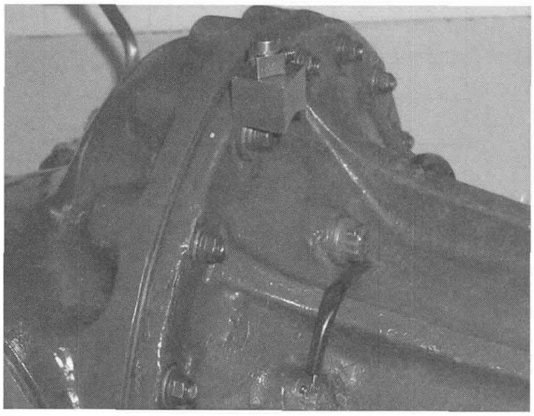


Fig. 1 (d). Accelerometer installation example at Lynx intermediate gearbox

Fig. 1 (e). Integrated test rig control room (Data Acquisition Room)

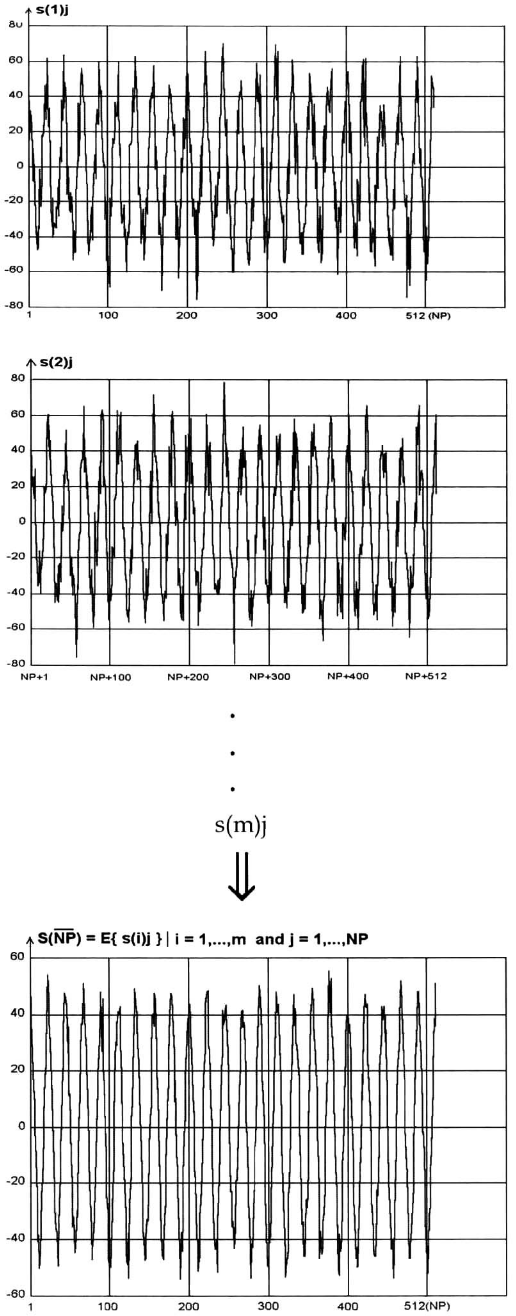
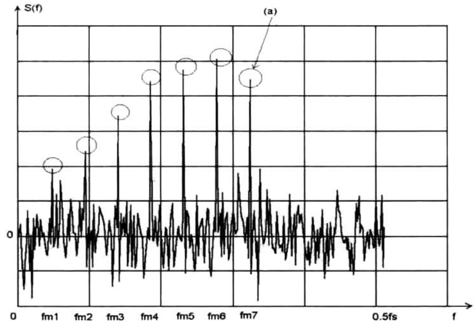


Fig. 2 (a). An example of signal averaging



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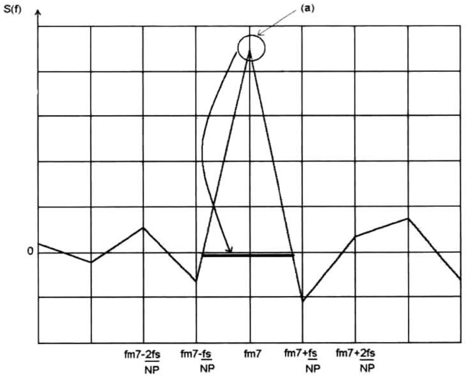
All the meshing frequency harmonic components on the frequency domain (peaks which is encircled in the above figure), the enhanced signal averaging suppress or smooth the peak amplitude to a mean of both side neighbor data points as follows :



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Inverse FFT of S(f)

Fig. 2 (b). An example of enhanced signal averaging

Table 1. A Set of Statistical Process Results

	Fig 4(a)	Fig 4(b)	Fig 5(a)	Fig 5(b)
Mean	-1.6798	-1.8607	-1.6798	-1.8607
Standard Deviation	28.2578	27.4119	6.1904	7.4683
M6	6.7483	7.3376	20.8317	67.6525
P-P	121.78	131.9935	41.8780	64.0128
	Fig 6(a)	Fig 6(b)	Fig 7(a)	Fig 7(b)
Mean	-0.1567	-0.1622	-0.0508	-0.0792
Standard Deviation	5.6149	9.9521	1.6967	2.4463
M6	6.6099	11.0452	16.8920	106.4297
P-P	26.7681	51.8175	13.1578	28.4236

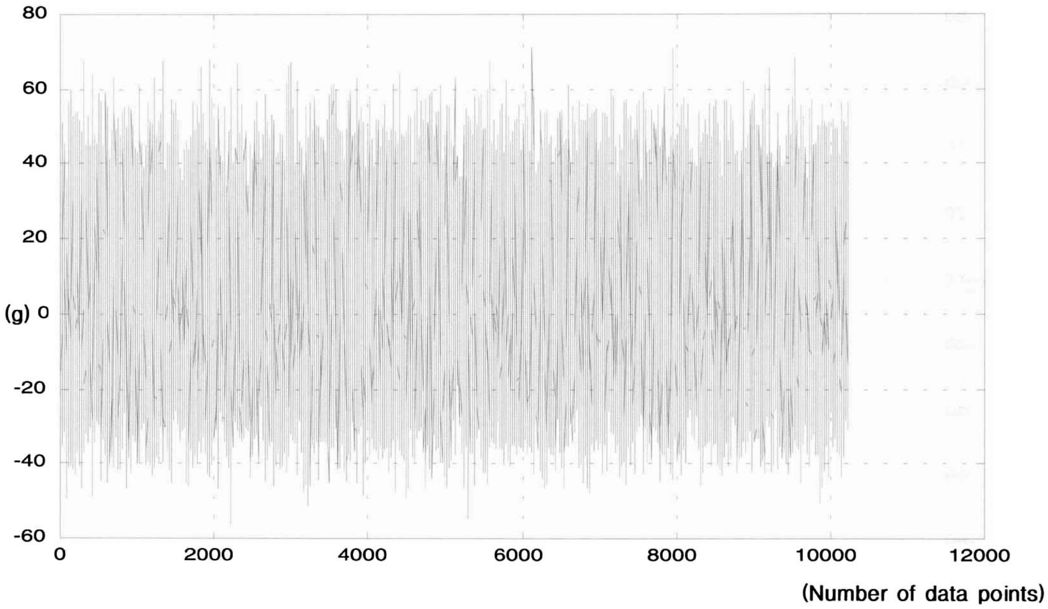

Fig. 3. Lynx intermediate gearbox raw vibration signal measured at the same position as A12 in Fig 1(a)

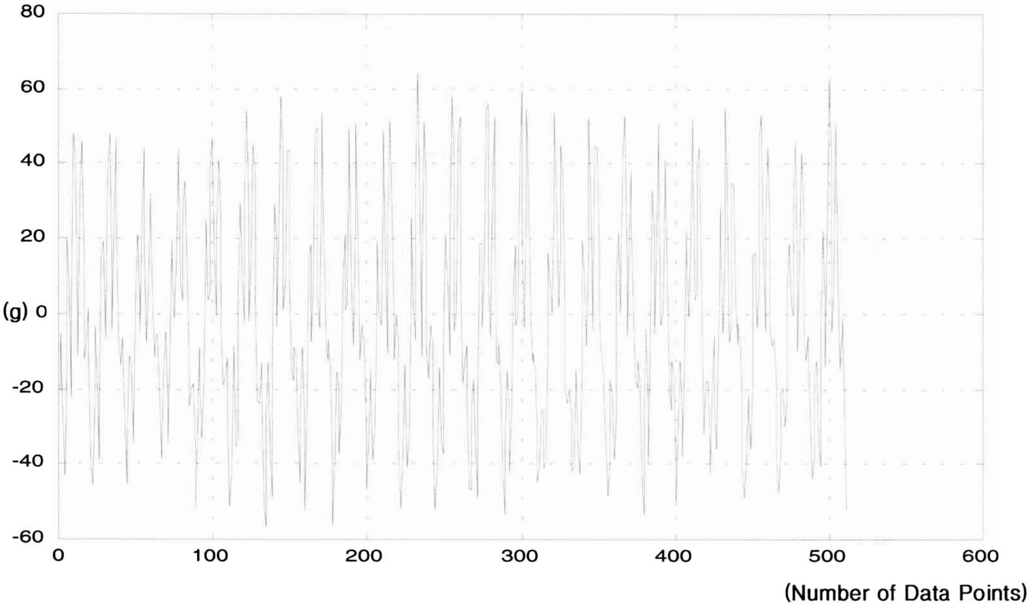

Fig. 4(a). Normal condition signal averaging signal data at a Lynx tail intermediate gearbox mesh point (i.e, Signal averaging of Fig 3 data)

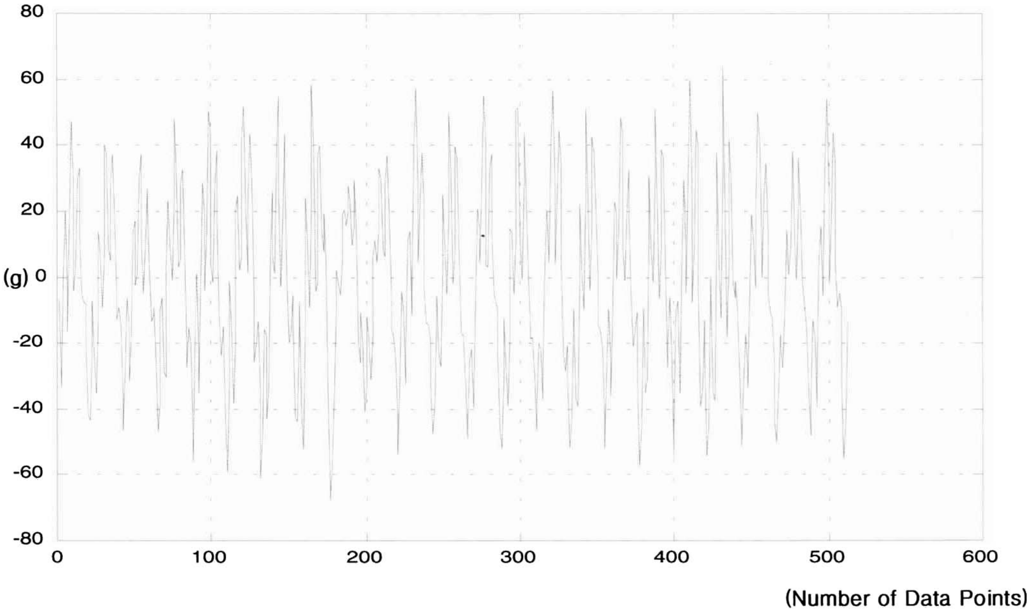

Fig. 4(b). Gear tooth defect condition signal averaging data at a Lynx tail intermediate gearbox mesh point

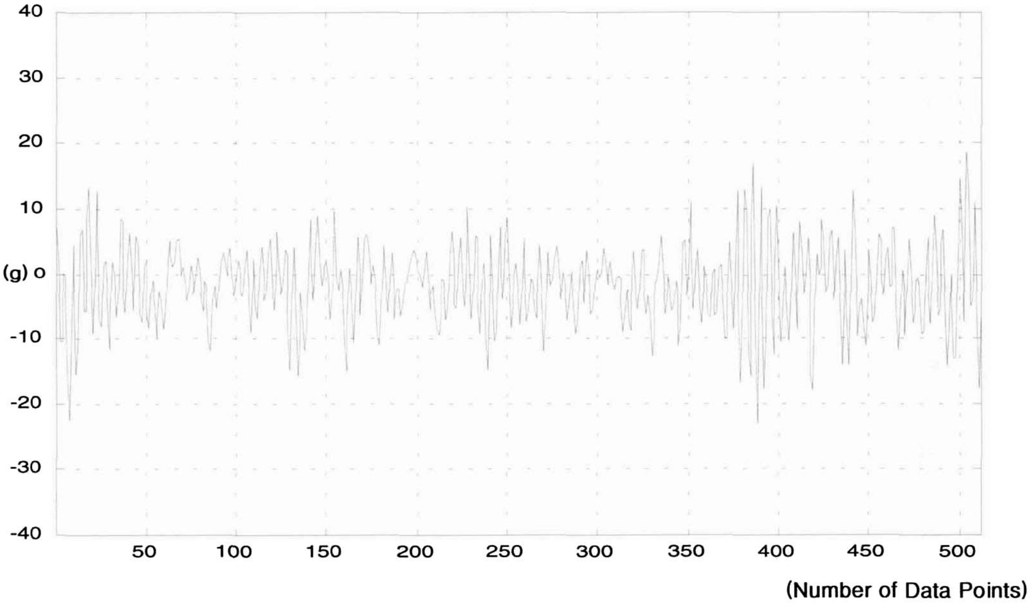

Fig. 5(a). Normal condition Enhanced signal averaging data of Lynx tail intermediate gearbox i.e, Frequency domain filtering of Fig 4(a)

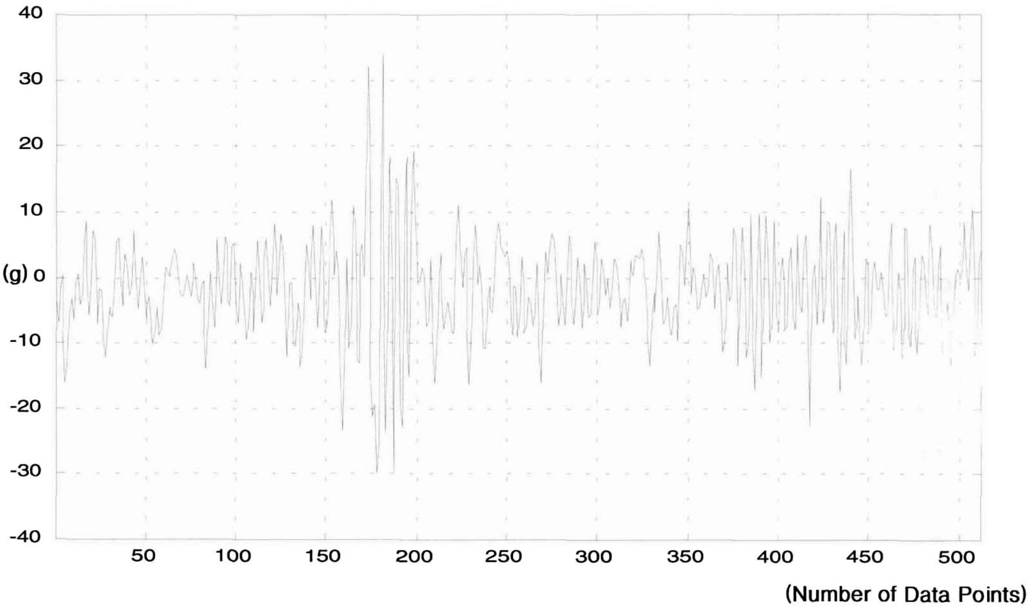

Fig. 5(b). Defect condition Enhanced signal averaging data of Lynx tail intermediate gearbox i.e, Frequency domain filtering of Fig 4(b)

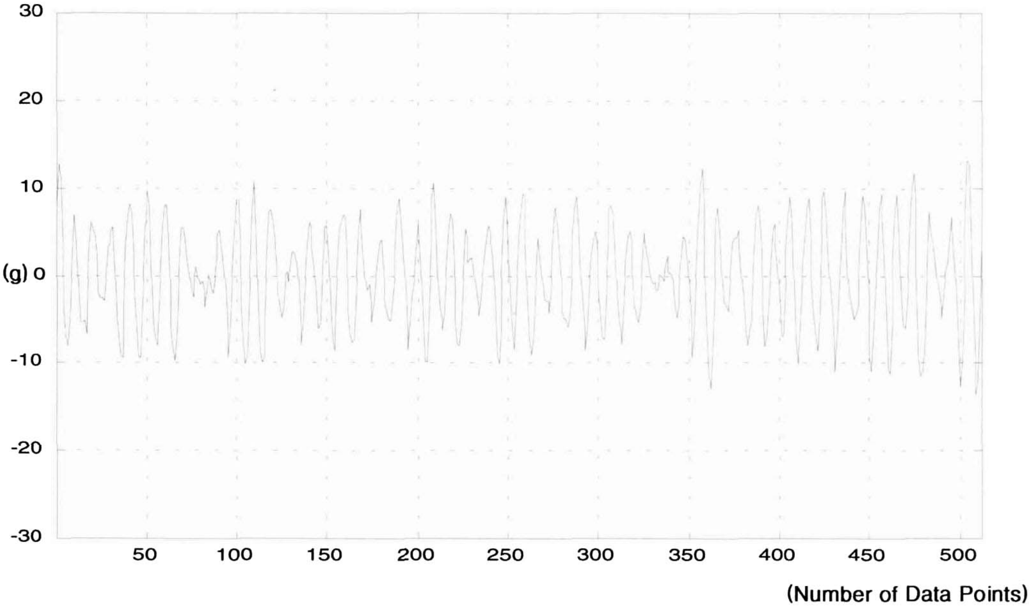

Fig. 6(a). Normal condition signal averaging data of EH101 Tail take-off shaft, measured at A07 in Fig 1(a)

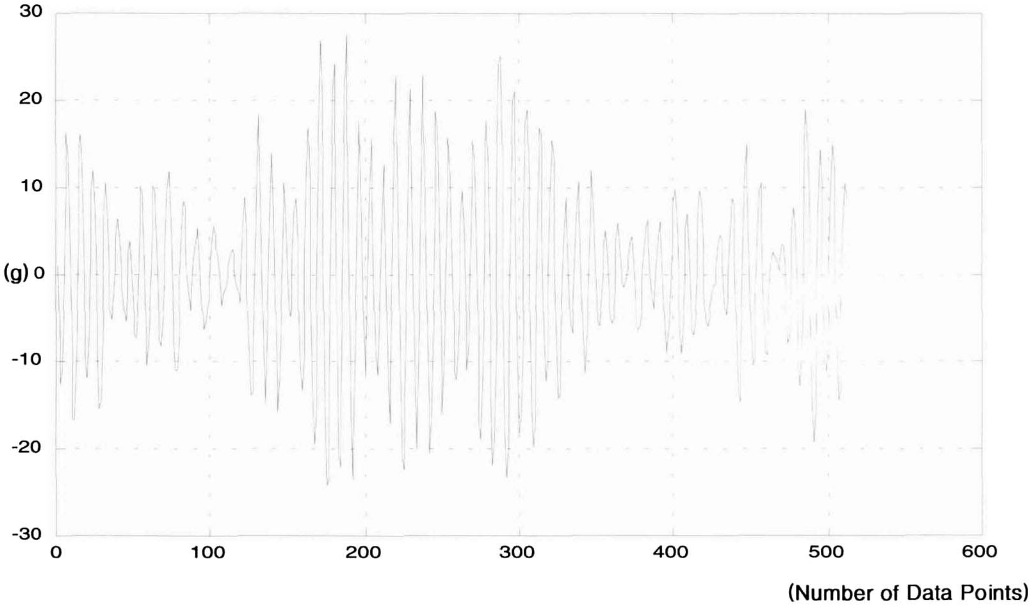

Fig. 6(b). Defect condition signal averaging data of EH101 Tail take-off shaft, measured at A07 in Fig 1(a)

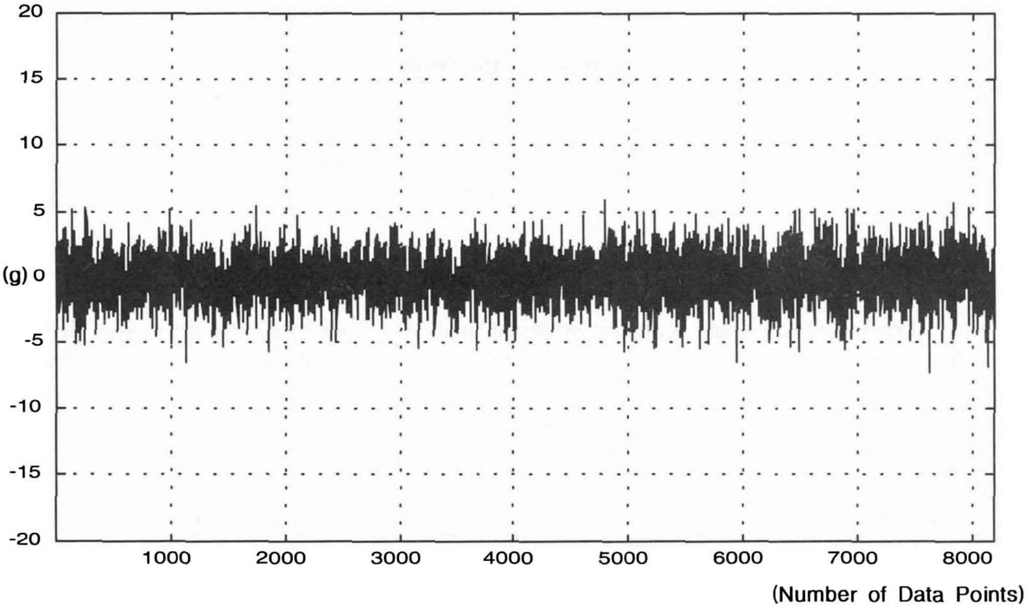

Fig. 7(a). Normal condition raw vibration signal at Lynx tail drive shaft Hanger bearing measured at the same position as A15 in Fig 1 (a)

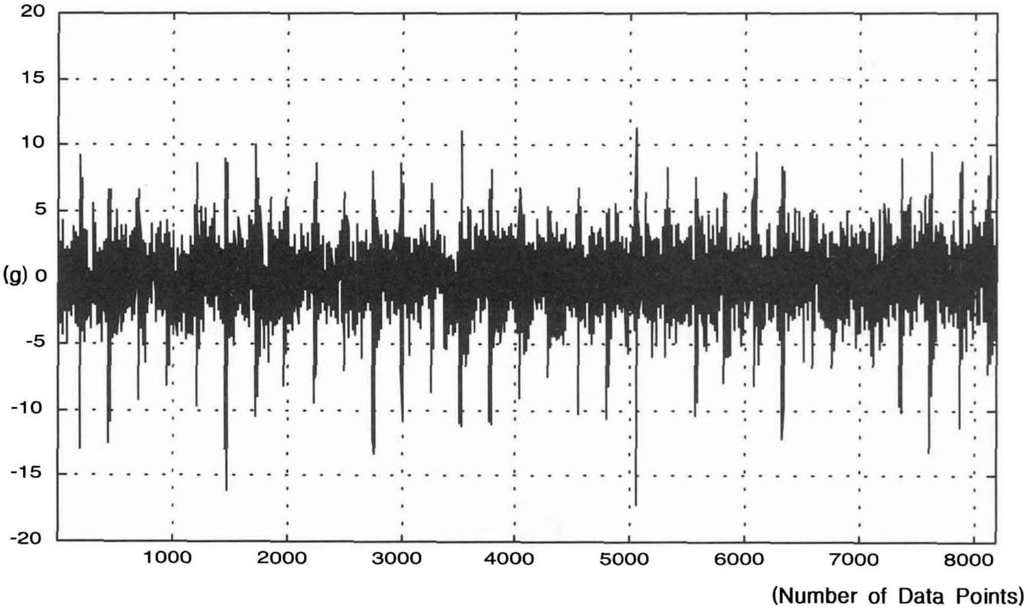

Fig. 7(b). Defect condition raw vibration signal at Lynx tail drive shaft Hanger bearing measured at the same position as A15 in Fig 1(a)