FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA
Invited Paper

REAL TIME PROCESSING OF VIBRATION SIGNALS WITH APPLICATION TO SLOW RUNNING GEARBOXES

Dr Krystof Kryniski
The Marcus Wallenberg Laboratory (MWL), KTH Stockholm

The work is focused on vibration monitoring techniques and processing methods devised for detecting cracks in the meshing zones of slow running. Then, the concept is extended to analyse a planetary gearbox. One of the major complications in monitoring any slow running gearboxes and planetary gear assemblies is the information overload. New methods are discussed which are capable of extracting and processing the vibration signals in real time. Some elements of architecture of a DSP processor are briefly reviewed, which are essential for understanding the methods developed and to appreciate their effectiveness. The actual implementation of the DSP processor based technique and the results obtained are included.

INTRODUCTION

Over the past few years advances in electronics have totally changed the concept of vibration monitoring. The current trend is to build-up a monitoring system capable of processing a large amount of data. It becomes apparent that the problem of today is not associated with the lack of information but with its extent. To avoid information overload new methods need to be devised which are capable of extracting and processing relevant information in real time.

The approach presented promotes such a concept by introducing the design of a stand-alone monitoring device, which can be programmed to track a specific machine problem. An on-board computer provides a flexible design capable of accommodating changes in software when any need to handle a different problem arises. Additionally, each device is equipped with a communication interface to link a number of devices into network which can be supervised by a host computer or any central monitoring system, when necessary. This is a very important aspect of the approach because the processing algorithms embedded in the device can be tested in the actual application and then, if successful, can be permanently attached to the commercial monitoring system operating on a plant. By shifting the computational power towards the sensor, the concept of DSP-processor based device offers an attractive solution to machine troubleshooting and diagnosis.

The approach also provides a challenge for research concerned with new measuring and processing techniques. Due to limitations imposed to produce a cost-effective solution, a very good understanding of a specific problem is required prior to the hardware and software design. It is essential to research the problem comprehensively and then optimise the processing techniques to be able to develop a highly dedicated device which can perform its job without compromising on accuracy and speed.

In the following work, the concept of a DSP-processor based device is presented with application to slow running gearboxes. Two different methods for detecting major faults in the gearboxes are discussed. The first method, referred to as a virtual stroboscopic technique, is viewed in relation to the local faults in the meshing zone such as cracks, spalls, broken teeth. The experimental results obtained on slow running gearboxes are presented. Next the extension of the method to monitor a planetary gear assembly is included. The second method discussed refers to the technique of monitoring distributed faults in gears, such as misalignment, unbalance, lack of lubrication or wear. By taking advantage of a circular buffering offered by the DSP processors, a very efficient and cost-effective implementation of a synchronous averaging technique is accomplished.

THEORETICAL BACKGROUND

Vibration analysis of the gearboxes is a well recognised and proven technique. There are a number of successful off-line applications developed for high-range speed machinery such as turbine gearboxes, helicopter gearboxes and automotive gearboxes. It has been shown that a crack in the meshing zone can be detected in its early stage by phase modulation [1,2]. Joined time-frequency techniques based on the short term Fourier transform (STFT) and Pseudo Wigner-Ville distribution (PWVD) were used to detect faults in the helicopter gearboxes [3,4,5]. One of the difficulties was insufficient resolution of a variety of signal components of different duration. The limitation of a fixed resolution was overcome with the wavelet transform [6] which was also applied to analyse the gearbox condition [7,8].

The concept of a joined time-frequency analysis provides a good diagnostic off-line tool for identifying different faults in the meshing zone. By comparing the frequency components in the different sections of the meshing zone both a distributed and local faults can be well isolated. The presence of a local fault such as spall, crack or broken tooth usually appears as short duration, high frequency transients. This signature becomes even more pronounced when the high frequency or ultrasonic sensors are in use.

Monitoring of slow running gears requires a slightly different approach than monitoring the gearboxes driving high-range speed machinery. Tracking of the gearbox angular position is difficult due to constantly varying speed and loading conditions. Harsh environment, high noise level and interference from other machines significantly effect the vibration spectra. However, perhaps the most serious problem met during monitoring any slow running gearbox is associated with the amount of information which is acquired per each revolution of a gear wheel. An example of a mill crusher gear illustrates the problem. A gear rotating with the speed of 3 RPM is still producing high frequency components in the range from 1 kHz to 10 kHz due to the presence of a spall or crack. To avoid aliaising and still be able to detect the high frequency components the sampling rate is required to be above 20 kHz. This results in more than 400,000 samples produced per each revolution of the gear. Of course with modern technology it is possible to handle data for a sufficient number of revolutions. However, a more efficient and cost effective approach is to apply the DSP solution and process the incoming information in real time.

THE DSP SOLUTION

A real time monitoring device is constructed around the DSP processor. Fig. 1 provides a schematic diagram of the device used for monitoring gearboxes. The DSP processor is responsible for controlling data acquisition, real time signal processing, data management and communication with the external devices and a host computer.

The algorithms for detecting different gearbox faults are stored on the PCMCIA memory card and downloaded when the power is switched on. The device can be easily reprogrammed to handle different tasks. The results of the analysis can be saved on the PCMCIA card and transferred to the host computer, when required.

By connecting the tachometer probes to the interrupts lines of a DSP processor the angular position of each gear wheel can be tracked with very high accuracy.

An analogue amplitude demodulator is added to the design to produce the envelope signal when measurements involve very high frequency or ultrasonic signals. The detector developed is capable of demodulating signals up to 10 MHz.

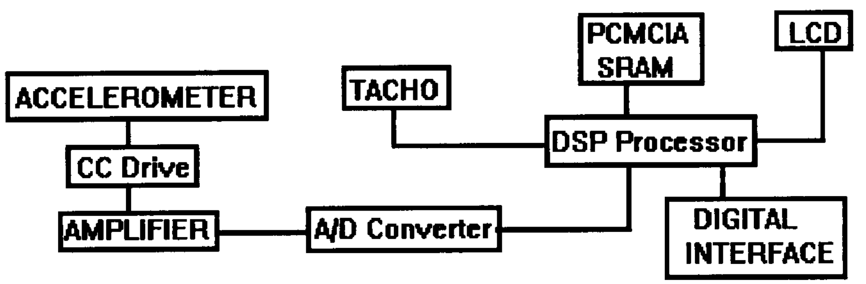

FIG.1

A prototype of the device for detecting local defects in the meshing zone was designed around the Motorola DSP56002EVM module. The device for monitoring distributed faults was originally developed with the Motorola DSP56002EVM module. However, it was re-designed to incorporate the Texas Instrument TMS320C31 DSP processor. Due to floating point calculations a number of operations were able to be performed more efficiently and accurately.

VIRTUAL STROBOSCOPIC METHOD

Off-line analysis of vibration signals revealed that any local defect in the meshing zone such as spall, crack or broken tooth produces short duration, high frequency transients. Therefore, the DSP solution is based on a device which is sensitive to the high frequency transients and which is designed to capture the moments of the detected transients. By timing the transients over a large number of gear rotations and tracking at the same time the rotational speed of any selected gear, the angular position where the transients are excited can be localised.

To visualise better the technique the trajectory of each gear wheel can be simulated. Then by flashing the gearbox with a "stroboscopic light" controlled by the timing information saved during the measurements, it should be possible to find a stationary point indicating a location of the fault.

The technique can be implemented on the DSP processor. The input capture functions can be engaged in tracking the rotational speed and registering the events of short duration, high frequency transients produced by a local fault. The DSP processor can also handle the high pass filtering and demodulation, when necessary. If the high frequency or ultrasonic sensors are in use it is recommended to use an analogue demodulator [9] to pre-process the acceleration signals.

A virtual stroboscopic technique was successfully applied to monitor slow running gearboxes. Fig. 2 shows the captured transient produced by a crack and its spectrum. Vibration was featured by a short duration signal occurring in the frequency range from 700 Hz to 2 kHz. It is apparent the amplitude of the transient significantly exceeds the amplitude of vibration produced by the gear in a crack free zone.

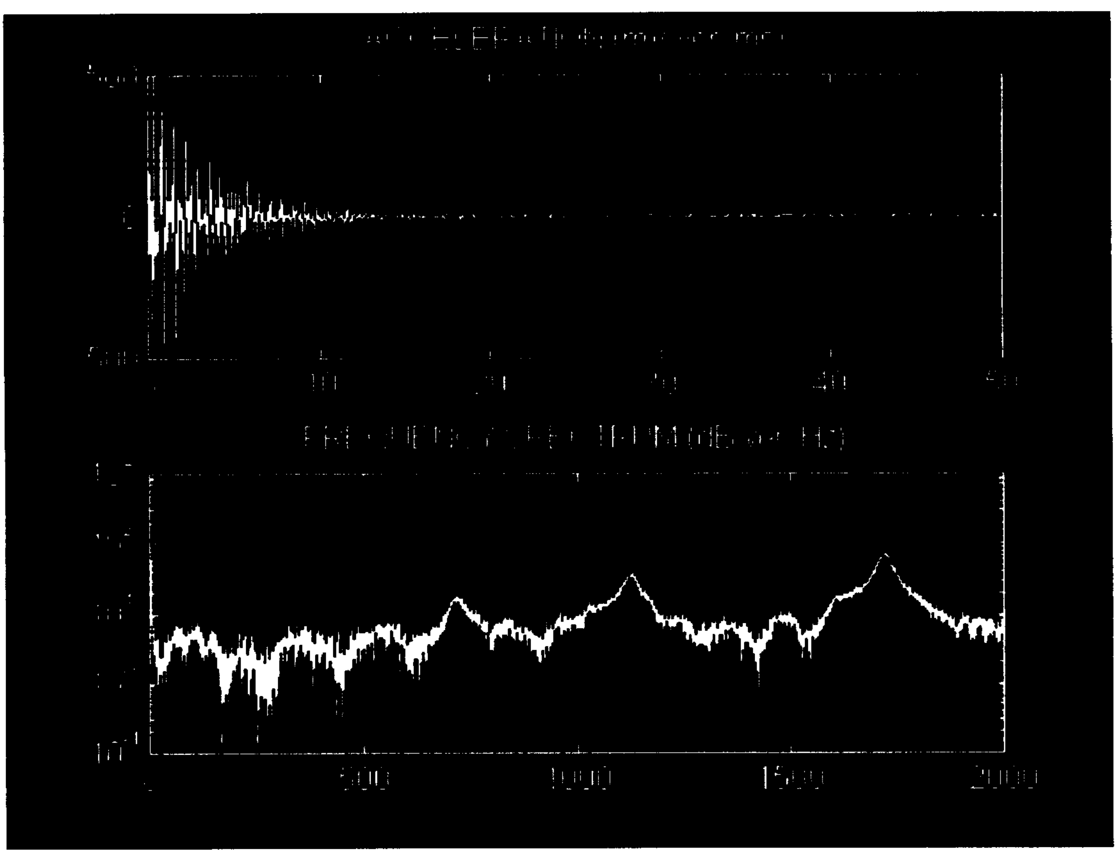

FIG. 2

The stroboscopic method can also be used for monitoring the condition of a planetary gear assembly. In the case of planetary gear the vibration level changes with the rotation of the planet wheel holder. When the planet gear moves towards the vibration transducer the vibration level increases. It reaches a peak level when the planet approaches the transducer, and then decreases as the planet gear recedes. Thus any transient produced by a local defect such as crack, spall or broken tooth is modulated by the movement of the planet wheel holder and a ring wheel. It is apparent that the short duration, high frequency transients produced by a faulty planet will be reappearing with a relatively low frequency. Some of them will not be detectable due to the modulation. An analysis of a planetary gearbox with the conventional method requires a large capacity of memory to handle data while real time signal processing provides a more efficient solution. By applying the stroboscopic method the time can be captured when short duration, high frequency transients are detected by a fixed sensor (e.g. accelerometer or ultrasonic sensor). By capturing the pulses produced by both the input shaft and ring shaft, the angular position of each element of a planetary gear can be traced. Then by calculating the times when the elements of the gear are coming into contact with each other and comparing these times with the occurrence of transients produced by a fault, the defected elements of the planetary gear can be identified. Again, to visualise how the method works the trajectories of the elements of a planetary gear need to be simulated. Fig. 3 (upper row) presents the trajectories of a planetary gear with the ring shaft and the input shaft moving in the same direction. Fig. 3 (bottom row) refers to the motion of the ring and input shafts moving in opposite directions.

Any local faults can be identified by flashing the "moving" elements of the gear with the "stroboscopic light". The local faults are pointed out by the stationary points.

SYNCHRONOUS AVERAGING METHOD

One of the major complications in monitoring slow running gearboxes is varying rotational speed. Due to the varying loading conditions it is unlikely that the speed of a gear will remain constant for more than a very short period of time. Thus, to identify and allocate any local or distributed fault in the meshing zone of the gearbox the vibration signals need to be measured with respect to the angular position of the gear. Of course, it is always possible to derive the pulses of an external clock from the optical encoders or passing tooth and then process information off-line. However, by implementing real time processing a more efficient and cost-effective solution can be achieved.

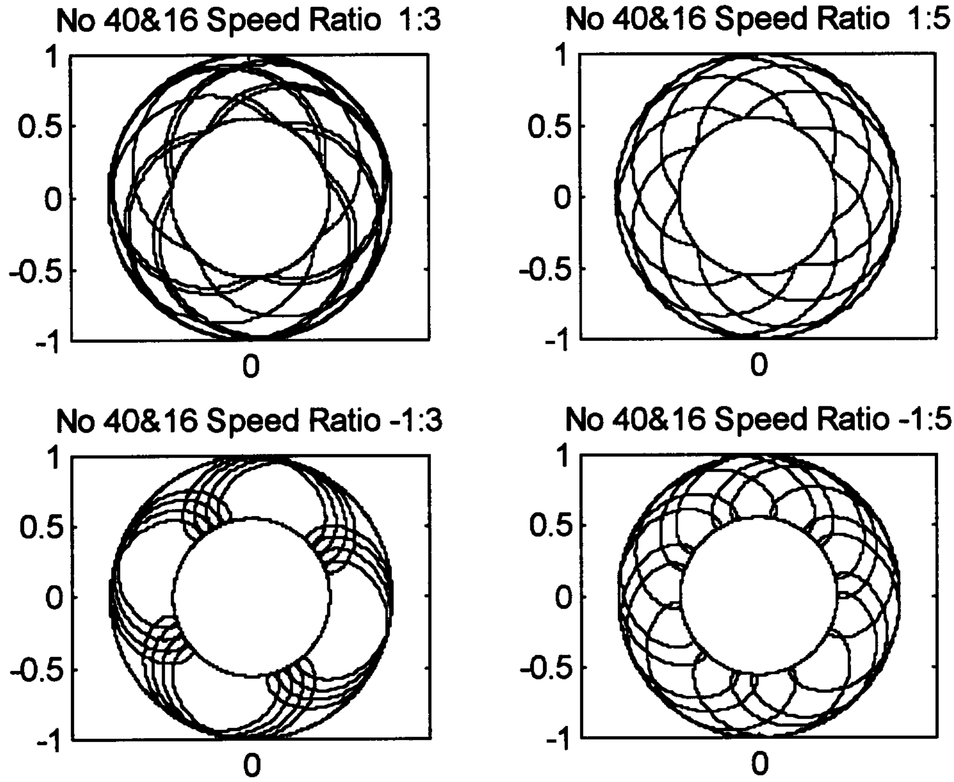

FIG. 3

A synchronous sampling rate cannot be derived prior to the measure of rotational speed. Thus, it is necessary to delay the processing till such a measure becomes available. The DSP processor offers a circular addressing mode, which enables the design of two rotating memories. One of them can be used as a buffer to store the incoming information, while the second one will keep the final results. The vibration signal can then be sampled with a fixed but high rate to produce the oversampled information which is temporarily saved in the first circular buffer. Then, when a tachometer signal is detected, an interrupt is generated to initialise the process of re-sampling with a rate corresponding to the detected rotational speed. The samples are interpolated at the same angular positions of the shaft so they can be respectively averaged and saved in the second buffer. Because the DSP processor averages the signal between the samples, the process of continuous data sampling is not effected. Providing that data acquisition is carried on with a sampling rate of 100 kHz, which is more than enough for most of gearbox applications, the DSP processor running with 40 MHz clock can execute more than 400 operations including interpolation, averaging, and if necessary, filtering and demodulation. Due to the circular memory arrangement, data which has already been processed, is overwritten by the new measures.

The technique successfully passed a number of experiments, showing a high immunity to noise. Frequency modulated signals with slow and fast varying rates were accurately restored without any phase and amplitude distortions.

REFERENCES

1. P.D. McFadden, Determining the location of fatigue crack in gears from phase of the change in the meshing zone, 1988, Mechanical Systems and Signal Processing, Vol.2, No.4.
2. J. Ma, C.J. Li, Gear defect detection through model-based wideband demodulation of vibrations, 1996, Mechanical Systems and Signal Processing, Vol 10, No.5.
3. B.D. Forrester, Time-frequency domain analysis of Helicopter transmission vibration, Aeronautical Research Laboratory, Melbourne, Australia, Report: ARL-PROP-R-180.
4. P.D. McFadden, Analysis of the vibration of the input bevel pinion in RAN Wessex helicopter main rotor gearbox WAK143 prior to failure, 1985, Aeronautical Research Laboratory, Melbourne, Australia, Report: ARL-PROP-R-169.
5. H. Oehlmann, D. Brie, M. Tomczak, A. Richard, A method for analysing gearbox faults using time-frequency representation, 1997, Mechanical Systems and Signal Processing, Vol II, No.4.
6. L.L. Schumaker, G. Webb, Recent advances in wavelet analysis, 1994, Academic Press, ISBN 0-12-632370-4.
7. W.J. Wang, P.D. McFadden, Application of wavelets to gearbox vibration signals for fault detection, 1996, Journal of Sound and Vibration, Vol. 192 No 5.
8. Staszewski, Application of the wavelet theory to fault detection in a spur gear, 1994, Mechanical Systems and Signal Processing, Vol.8, No. 3.
9. K. Kryniski, Monitoring rolling element bearings of twin-screw compressor unit, 1993, ABB Stal Refrigeration, Norrköping, Sweden, ISRN KTH/FKT/FR-93/15-S.