SYSTEMS AND METHODS FOR SELF-SYNCHRONIZED DIGITAL SAMPLING

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ABSTRACT

Systems and methods for self-synchronized data sampling are provided. In one embodiment, a system for capturing synchronous data samples is provided. The system includes an analog to digital converter adapted to capture signals from one or more sensors and convert the signals into a stream of digital data samples at a sampling frequency determined by a rotational frequency signal from a rotating machine, wherein the synchronizer is further adapted to generate a sampling control signal and wherein the sampling control signal is based on the rotational frequency signal.

25 Claims, 2 Drawing Sheets
Fig. 1

- Band Pass Filter
- Low Pass Filter
- Variable Oscillator
- Frequency Divider
- PLL
- Synchronizer
- Sensors
- Sensor Signals
- Accelerometer Signal Sampled at $f_s$
- Digital Signal Processor

Rotating Machinery

(f_R)

$105$

$110$

$115$

$142$

$144$

$146$

$148$

$149$

$120$

$125$

$130$

$100$
Receiving a rotational frequency signal from rotating machinery

Generating a sampling control signal based on the rotational frequency signal

Capturing one or more signals at a sampling frequency provided by the sampling control signal

Analyzing synchronous data samples.

Fig. 2
SYSTEMS AND METHODS FOR SELF-SYNCHRONIZED DIGITAL SAMPLING

GoverNMENT LICENSE RIGHTS

The U.S. Government may have certain rights in the present invention as provided for by the terms of Contract No. NAS8-01140 awarded by NASA.

TECHNICAL FIELD

The present invention generally relates to digital sampling and more particularly to capturing synchronous data samples.

BACKGROUND

Coherent Phase Line Enhancement (CPLE) is a technique for analyzing spectral characteristics of high speed rotating turbine machinery. The CPLE technique is employed because of its benefits for detecting synchronous and harmonic phenomena. For example, for the main engines of the Space Shuttle, accelerometers are used to sense vibration within pumps and turbines. Frequency analysis through fast Fourier transforms of the accelerometer data are used to detect, predict, and avoid potentially catastrophic engine failures. For example, vibrations within rotating machinery, occurring at first, second, third, or some other Nth harmonic of the rotational frequency can alone, or in combination, indicate current operating conditions within the machinery. These indications can further indicate the degradation of internal components, such as a bearing failure, which if left uncorrected, will result in further degradation or failure of the machinery. Therefore, when using CPLE, it is highly desirable to have to the accelerometer output sampled synchronously at a frequency which is proportional to the rotational speed of the rotating shaft, engine, pump, turbine or similar rotating machinery component.

Using techniques available in the art today, the sampling time of the accelerometer signal is estimated and the physically sampled data is interpolated back to desired synchronous sampling points to obtain a synchronous data set. Unfortunately, both the estimated synchronous sampling times and the data interpolation introduce errors into the analysis. In addition to producing errors, estimation of the sampling times and data interpolation functions also increase onboard data processing requirements. Further, problems with estimating shaft rotation and calculating interpolated accelerometer samples are exacerbated when the machinery is starting up and when the machinery is slowing down because the rotational speed of the machine is changing. For high speed rotating turbine machinery, start-up and slow-down are critical periods of operation for detecting, predicting, and avoiding failures. For performing an analysis such as CPLE, it is highly desirable to eliminate these sources of errors and the associated processing requirements.

For the reasons stated above and for other reasons stated below which will become apparent to those skilled in the art upon reading and understanding the specification, there is a need in the art for systems and methods for synchronizing digital sampling having reduced error levels compared to existing techniques.

SUMMARY

The embodiments of the present invention provide methods and systems for self-synchronized digital sampling, and will be understood by reading and studying the following specification.
Embodiments of the present invention are directed to a method for performing vibration analysis for rotating machinery, using a signal having a frequency proportional to the rotational speed of the machinery. The method may include the following steps: (1) capturing a signal from the machinery, (2) converting the signal to analog form, (3) filtering the signal to remove noise, (4) performing frequency analysis on the filtered signal, and (5) outputting the results of the analysis.

In one embodiment, the signal is captured from one or more sensors attached to the machinery. The sensors may include accelerometers, strain gauges, or other types of transducers. The signal is then converted to an analog form using an analog/digital (A/D) converter. The analog signal is then filtered using a low-pass filter to remove high-frequency noise. The filtered signal is then fed into a phase-locked loop (PLL) circuit, which locks onto the frequency of the incoming signal and generates a control signal proportional to the rotational speed of the machinery. The control signal is then converted to a digital signal using a digital/analog (D/A) converter and outputted for further analysis.

In another embodiment, the signal is captured directly from the machinery using a matched filter. The matched filter is designed to match the frequency response of the machinery and outputs a signal proportional to the rotational speed of the machinery. The output signal is then fed into a PLL circuit, which locks onto the frequency of the incoming signal and generates a control signal proportional to the rotational speed of the machinery. The control signal is then converted to a digital signal using a D/A converter and outputted for further analysis.

In both embodiments, the control signal is outputted at a frequency that is proportional to the rotational speed of the machinery. This allows for accurate and efficient vibration analysis of rotating machinery, regardless of the type or size of the machinery. The method described herein has numerous applications in industries such as aerospace, automotive, and power generation, where accurate vibration analysis is crucial for maintaining the safety and reliability of rotating machinery.
example, in one embodiment, bandpass filter 115 blocks the input signal from rotational machinery 105 when rotational machinery 105 is rotating at significantly less than operating speed. This would most frequently occur when rotational machinery 105 has just started and is accelerating up to operating speed, or when machinery 105 has been turned off and is decelerating down to rest speed. During these periods, as described above, variable oscillator 146 outputs a nominal frequency, f\text{nominal}, to A/D converter 120. Providing a nominal frequency sampling control signal to A/D converter 120 allows system 100 to continue to monitor for vibrations using a sampling frequency sufficient to satisfy frequency analysis resolution requirements and the minimum Nyquist rate, when rotational machinery 105 is running at significantly less than operation speed. In the case of a space shuttle engine, this allows vibration sensing and analysis prior to engine start and after engine shutdown to detect “popping” explosions caused by the igniting of leaked or unburned Oxygen.

As previously discussed, embodiments of the present invention provided synchronous data samples for performing frequency analysis of high speed rotating turbine machinery by directly coordinating the capture of accelerometer data samples with the rotation of the machinery under analysis. As would be appreciated by one skilled in the art, CPLE is one example of such a technique for analyzing the spectral characteristics of high speed rotating turbine machinery. FIG. 2 is a flow chart illustrating a method of synchronous data frequency analysis of one embodiment of the present invention. The method starts at 210 with receiving a rotational frequency signal from a piece of rotational machinery. In one embodiment, the rotational machinery produces and outputs the rotational frequency signal as a sequence of one or more pulses for each rotation of a shaft within the rotational machinery. In one embodiment, the rotational machinery outputs N1 pulses for each revolution of the shaft. In one embodiment, receiving a rotational frequency includes receiving the sequence of one or more pulses where the speed of the shaft is represented by the period of, or the timing between pulses. The method then proceeds to 220 with generating a sampling control signal. In one embodiment, the sampling control signal provides a sampling frequency that is proportional to the rotational frequency of the rotating machinery. In one embodiment, the sampling control signal is a voltage signal having a frequency equal to the rotational frequency multiplied by a constant, N2. One skilled in the art upon reading this specification would appreciate that a value for N2 is readily determined based on the resolution requirements of the particular frequency analysis being performed, and satisfying the minimum Nyquist rate.

In one embodiment, generating a sampling control signal is accomplished by providing the rotational frequency signal from the rotating machine to the input of a phase locked loop and outputting the sampling control signal from the phase locked loop. In one embodiment, where the phase locked loop comprises a multiplier, a variable oscillator, and a frequency divider, the method further comprises multiplying the rotational frequency signal with a frequency-divided output of the variable oscillator. The frequency of the variable oscillator output is then varied based on this product. In one embodiment, the frequency of the variable oscillator output is set to a nominal frequency in the absence of a rotational frequency signal. In one embodiment, the frequency of the variable oscillator output is set to the nominal frequency when the rotational frequency signal indicates that the rotating machine is operating at significantly less than its normal operating speed.

The method next continues to 230 with capturing one or more signals at a frequency equal to the sampling frequency. In one embodiment, capturing one or more signals comprises driving an A/D converter to capture the one or more signals at the sampling frequency. In one embodiment, capturing one or more signals comprises producing a sequence of synchronous data samples based on one or more signals. In one embodiment, the one or more signals are produced by one or more accelerometers. In one embodiment, the one or more signals are produced by one or more accelerometers located on the rotating machinery. By capturing signals at the sampling frequency, the data samples captured from the signals are thus synchronous with the rotational frequency of the rotating machinery. In one embodiment, the method proceeds to 240 with analyzing the synchronous data samples. The output of the A/D converter is a stream of data samples that are synchronous with the rotation of the rotating machinery, thus allowing direct analysis of the data in the frequency domain, without requiring re-sampling of the data (i.e., estimating sampling times and interpolating sensor signal data to calculate a synchronous data set) and without incurring the associated calculation time, ambiguities and errors. Vibrations within the rotating machinery, occurring at a first, second, third, or some other Nth harmonic of the rotational frequency either alone, or in combination are readily correlated with an FFT of the synchronous data samples with knowledge of constants N1 and N2 by one skilled in the art upon studying this specification.

Several means are available to implement the synchronizer discussed above. These means include, but are not limited to, digital computer systems, programmable controllers, or field programmable gate arrays. Therefore other embodiments of the present invention are program instructions resident on computer readable media which when implemented by such processors, enable the processors to implement embodiments of the present invention. Computer readable media include any form of computer memory, including but not limited to punch cards, magnetic disk or tape, any optical data storage system, flash read only memory (ROM), non-volatile ROM, programmable ROM (PROM), erasable-programmable ROM (E-PROM), random access memory (RAM), or any other form of permanent, semi-permanent, or temporary memory storage system or device. Program instructions include, but are not limited to computer-executable instructions executed by computer system processors and hardware description languages such as Very High Speed Integrated Circuit (VHISIC) Hardware Description Language (VHDL).

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement, which is calculated to achieve the same purpose, may be substituted for the specific embodiment shown. This application is intended to cover any adaptations or variations of the present invention. Therefore, it is manifestly intended that this invention be limited only by the claims and the equivalents thereof:

What is claimed is:

1. A method for synchronous data frequency analysis, the method comprising:

   receiving a rotational frequency signal representing a rotational frequency of a rotating machine;

   generating a sampling control signal based on the rotational frequency signal;

   capturing one or more signals at a sampling frequency based on the sampling control signal to produce a sequence of synchronized data samples; and

   analyzing the sequence of synchronized data samples;
wherein when the rotational frequency indicates the rotating machine is operating at a normal operating speed, the sampling frequency is proportional to the rotational frequency of the rotating machine; and

wherein when the rotational frequency indicates the rotating machine is operating at below the normal operating speed, the sampling frequency is equal to a nominal sampling frequency.

2. The method of claim 1 further comprising:
generating the one or more signals from one or more accelerometers located on the rotating machine.

3. The method of claim 1 further comprising:
generating the one or more signals from one or more sensors.

4. The method of claim 1 further comprising:
analyzing a Fourier transform of the sequence of synchronized data samples.

5. The method of claim 1, wherein the sampling frequency is proportional to the rotational frequency of the rotating machine.

6. The method of claim 5, wherein the sampling frequency is proportioned to satisfy a Nyquist rate with respect to the rotational frequency of the rotating machine.

7. The method of claim 1 further comprising:
filtering the rotational frequency signal, wherein harmonics greater than a fundamental harmonic are removed from the rotational frequency signal.

8. The method of claim 1 further comprising:
filtering the rotational frequency signal, wherein harmonics less than a fundamental harmonic produced by the rotating machine when the rotating machine is running at a normal operating speed are removed from the rotational frequency signal.

9. The method of claim 1, wherein generating a sampling control signal further comprises:
receiving the rotational frequency signal with a phase locked loop; and
outputting the sampling control signal from the phase locked loop.

10. A system for capturing synchronous data samples, the system comprising:
an analog to digital converter adapted to capture signals from one or more sensors and convert the signals into a stream of digital data samples at a sampling frequency determined by a sampling control signal; and
a synchronizer coupled to the analog to digital converter and adapted to receive a rotational frequency signal from a rotating machine, wherein the synchronizer is further adapted to generate the sampling control signal, wherein the sampling control signal is based on the rotational frequency signal, the synchronizer comprising:
a phase lock loop circuit adapted to input the rotational frequency signal and output the sampling control signal, wherein the sampling control signal is synchronized with the rotational frequency signal, the phase lock loop circuit comprising:
a variable oscillator coupled to the analog to digital converter and adapted to output the sampling control signal;
a first frequency divider adapted to output a first signal representing the frequency of the sampling control signal divided by a constant; and
a multiplier adapted to multiply the rotational frequency signal with the first signal;

wherein the variable oscillator varies a frequency of the sampling control signal based on a product of the rotational frequency signal and the first signal.

11. The system of claim 10, wherein the synchronizer generates a sampling control signal that results in the sampling frequency being proportional to a rotational frequency of the rotating machine.

12. The system of claim 11, wherein the synchronizer generates a sampling control signal that results in the sampling frequency satisfying a minimum Nyquist rate with respect to the rotational frequency of the rotating machine.

13. The system of claim 10, the synchronizer further comprising:
a second frequency divider adapted to input the sampling control signal from the variable oscillator and reduce the sampling frequency of the sampling control signal by a constant.

14. The system of claim 10, further comprising:
a low pass filter adapted to filter the product of the rotational frequency signal and the first signal and communicate a second signal to the variable oscillator based on the product of the rotational frequency signal and the first signal; and
wherein the variable oscillator varies a frequency of the sampling control signal based on the second signal.

15. The system of claim 14, wherein the low pass filter communicates only a lower sideband of the product of the rotational frequency signal and the first signal to the variable oscillator.

16. The system of claim 10 further comprising:
a bandpass filter adapted to filter from the rotational frequency signal harmonics less than a fundamental harmonic produced when the rotating machine is running at a normal operating speed; and
wherein the bandpass filter is further adapted to filter from the rotational frequency signal harmonics greater than the fundamental harmonic.

17. The system of claim 10, wherein when the rotational frequency signal indicates the rotating machine is operating at a normal operating speed, the synchronizer generates a sampling control signal that results in the sampling frequency being based on a rotational frequency of the rotating machine; and

when the rotational frequency signal indicates the rotating machine is operating at less than normal operating speed, the synchronizer generates a sampling control signal that results in the sampling frequency being equal to a nominal sampling frequency.

18. The system of claim 10 further comprising:
a digital signal processor adapted to input the stream of digital data samples and perform one or more frequency analyses based on the stream of digital data samples.

19. A system for analyzing synchronous data, the system comprising:
means for generating a sampling control signal based on a rotational frequency of a rotating machine; and
means for converting one or more sensor signals into a sequence of data samples based on the sampling control signal, the means for converting responsive to the means for generating:
wherein when a rotational frequency signal indicates the rotating machine is operating at a normal operating speed, a sampling control signal is generated that results in a sampling frequency being based on the rotational frequency of the rotating machine; and
wherein when the rotational frequency signal indicates the rotating machine is operating at less than normal oper-
ating speed, a sampling control signal is generated that
results in the sampling frequency being equal to a nomi-
nal sampling frequency.

20. The system of claim 19 further comprising:
means for analyzing the sequence of data samples.

21. The system of claim 19, wherein the means for gener-
ating a sampling control signal generates a sampling control
signal comprising a sampling frequency that is proportional
to the rotational frequency of the rotating machine.

22. The system of claim 21, wherein the means for gener-
ating a sampling control signal generates a sampling control
signal comprising a sampling frequency satisfying a mini-
imum Nyquist rate with respect to the rotational frequency of
the rotating machine.

23. A computer-readable medium having computer-ex-
ecutable instructions for performing a method for synchro-
nous data frequency analysis, the method comprising:
receiving a rotational frequency signal representing a rota-
tional frequency of a rotating machine; and

generating a sampling control signal based on the rota-
tional frequency signal;
wherein when the rotational frequency indicates the rotat-
ing machine is operating at a normal operating speed, a
sampling frequency is proportional to the rotational fre-
quency of the rotating machine; and
wherein when the rotational frequency indicates the rotat-
ing machine is operating at below the normal operating
speed, the sampling frequency is equal to a nominal
sampling frequency.

24. The computer-readable medium of claim 23, wherein
the method further comprises:
capturing one or more signals at a sampling frequency
based on the sampling control signal to produce a
sequence of synchronized data samples.

25. The computer-readable medium of claim 24, wherein
the method further comprises:
analyzing a Fourier transform of the sequence of synchro-
nized data samples.