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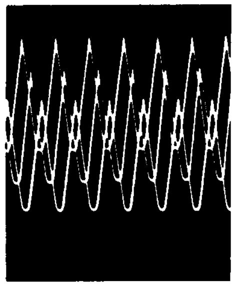

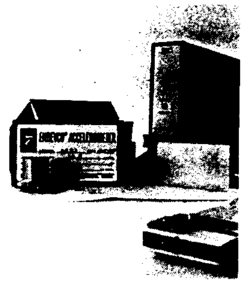

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DIGITAL EVM: THE NEXT STEP IN AIRBORNE ON-CONDITION MONITORING SYSTEMS

AUTHORS: HARRY BRAY AND DAVE RAY
ENDEVCO

ABSTRACT

The use of microprocessor control and digital data processing affords substantial improvements in utility and reliability in this new airborne engine vibration monitoring system. Data reliability is substantially enhanced through the use of a digital narrow-band filter synchronized with engine RPM and through incorporation of a continuous self-test or "system health" algorithm. Supplemental output allows trending of vibration data as well as in-flight calculations of re-balance information.

INTRODUCTION

Before the next generation of engine vibration monitoring equipment was designed, a study was conducted to determine what the expectations of the system were. This revealed an interesting list of requirements that could only be met by designing a system that could determine the integrity of the signal, perform diagnostic checks ensuring the system was functioning properly, and make calculations on the signal to perform the engine diagnostics that engine vibration potentially can provide. These tasks could only be performed with a digital system. The first part of this paper discusses in detail the expectations of an engine vibration monitoring system. The second part discusses how these expectations were met through the implementation of a digital system. Because it is essential that anyone considering an engine monitoring system today understand the advantages gained by implementing a digital filter technique versus an analog technique, some time is also spent in discussing digital filtering.

SYSTEM EXPECTATIONS

Expectations of an airborne vibration monitoring system are deemed to be as follows:

A. Meet on-condition maintenance system requirements:

   On condition maintenance (OCM) relies for its success on the replacement of parts only when necessary and not strictly based on time between overhaul (TBO) schedules. To achieve this requires reliable monitoring of engine vibration.

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B. Keep unscheduled engine removals (UER) and in-flight shutdowns (IFSD) to a minimum:

An airborne vibration monitoring system should perform the necessary data acquisition and diagnostics to enable the inspection and the scheduling of component replacements within the allowable time and economics necessary to control IFSD, UER, delays and cancellations.

C. Prevent secondary damage:

Damage caused to accessories by a "high shaker" and excessive internal damage due to a problem not detected should be prevented.

D. Aid in-shop action planning during engine removal:

A system utilizing state-of-the art computing capability should perform sufficient diagnostics to assist maintenance in analyzing problems before engine removal, thereby minimizing troubleshooting and repair time.

BENEFITS OF DESIGNING A DIGITAL ENGINE VIBRATION MONITORING SYSTEM

A vibration monitoring system can meet these expectations only if it performs reliably, assists in assuring vibration levels are well within limits, and provides computational power to reduce the raw data to key bits of information that provide a data base on individual engines.

Based on the previous history of analog systems and realizing the limited amount of analysis available with analog circuit design, it was determined that a digital system was required enabling the following:

A. Improved data reliability through

- Increased signal-to-noise ratios by digital "narrow-banding"
- Automatic signal evaluation and averaging, assuring only data with a high degree of confidence is displayed
- Better discrimination against system malfunction

B. Digital processing to compute in-flight on-wing balance information because:

- Balance determined under actual flight conditions results in lower vibration levels
- Balance determined in-flight or on-wing saves manhours, since equipment is always installed and ground run-ups are reduced
- A time correlation of change in balance may be documented

C. A data base on individual engines could be computed and stored to:

- Develop norms for engine types
- Characterize pecularities of individual engines
- Enable trending of engine characteristics
- Record real time data for subsequent analysis

THE SERIES 6670 DIGITAL NARROW-BAND FILTER SYSTEM

A simplified block diagram of the synchronous digital narrowband filter system necessary to perform these tasks is shown in Figure 1. A tach signal from the engine is conditioned and fed to a microcomputer-based tach ratio generator. The output pulses of the tach generator are used to control a digital narrowband filter. The accelerometer's input vibration signal is conditioned and fed through the narrowband filter clocked to the input tach signal. The result is a greatly increased signal-to-noise ratio of the input signal that is presented to the flight deck display, to the microcomputer for further processing and to the on-board data recorder. The basic system is packaged in a 1/2 ATR (4 MCU) box and contains all the circuitry required for eight vibration signals and up to nine tachmometer signals. A four channel system is available in a 3/8 ATR (3 MCU) enclosure. The data recorder is a solid state recorder with a one megabit storage capability housed in a separate 1/4 ATR box.

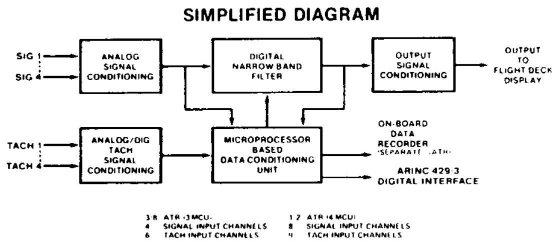

Figure 1. Simplified block diagram of Series 6670 Digital On Condition Engine Vibration Monitor

The following paragraphs describe each of the blocks shown in the simplified diagram.

Digital Narrow-Band Filter

One of the reasons given previously for implementing a digital synchronous narrowband filter instead of an analog filter was to increase data reliability. Data reliability is enhanced to a much higher degree because filter accuracy is determined by the number of bits instead of how well tuned as in analog systems, and by the filter's ability to discriminate the signal of interest from a complex signal containing a high noise component.

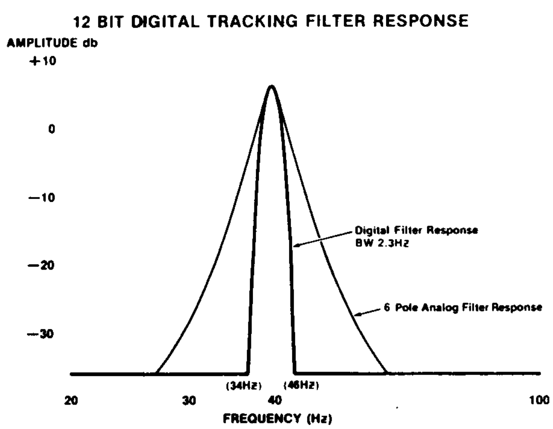

Figure 2. Comparison of the attenuation characteristics of a Digital Tracking Filter to an analog filter.

Figure 2 compares the filter characteristics of a 6-pole analog filter (3 poles per side) and a 12-bit digital tracking filter using an 8-bit digital-to-analog converter on the output. From the diagram it is easy to see the improved characteristic. A 12-bit D/A presents an even more impressive characteristic by individual filters being down 60 dB at essentially the same 34 Hz and 46 Hz frequencies. With this type of stopband performance the noise suppression outside the passband is greatly enhanced as shown in Table 1.

TABLE 1. DIGITAL VS ANALOG COMPARISON

	TYPICAL ANALOG 6-POLE FILTER (3 POLES PER SIDE)	DIGITAL 12-BIT FILTER
PASSBAND 3 dB (% OF C.F.)	5%	5%
STOPBAND	18 DB/OCT	60 DB AT ONE OCTAVE
NOISE SUPPRESSION OUTSIDE PASSBAND	LESS THAN 10:1 PER OCTAVE	1000:1 WITHIN ONE OCTAVE
SHAPE FACTOR	≈15	≈ 8

With a 1000:1 suppression outside the passband, a signal may be discriminated from a composite of noise plus signal where the signal of interest is of such low amplitude that it is not recognizable. This is shown in Figure 3 where a broadband signal (upper oscilloscope trace) containing twice as much noise power as signal power is presented to the input of the digital narrowband filter. The output of the digital filter, shown in the lower trace, is essentially noise-free.

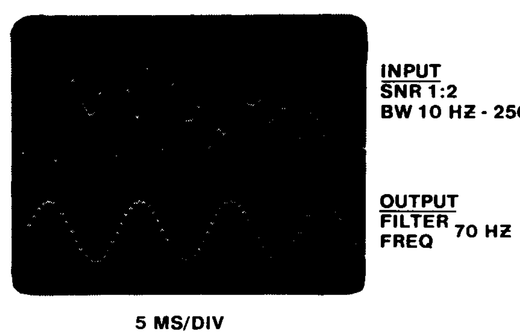

Figure 3. Oscilloscope traces showing ability of a Digital Tracking Filter to extract an engine rotational vibration from overall engine vibration.

Digital Nonrecursive Filter

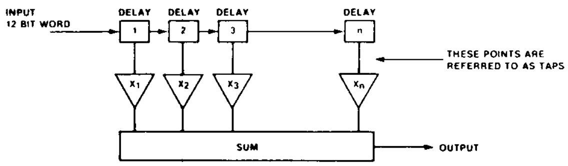

Figure 4 Block diagram of a nonrecursive digital filter

The type of filter that has been implemented is a nonrecursive digital filter. A block diagram of this type of filter is shown in Figure 4. The input signal is sampled and fed through an analog-to-digital converter and then shifted into the delay blocks shown.

As each sample is shifted through "n" delay blocks, it is multiplied by a weighting factor and summed with "n-1" other samples, each of which has been multiplied by a separate weighting factor, to produce an output sample. Consider two input sine waves of "f" and "2f" where the filter is centered about "2f" and the signal is sampled 50 times per 360° of the "2f" component. Assume X has a weighting function of 1, and 50 delay blocks later X_{50} has a weighting function of 1. The result of this condition on the "2f" wave, when multiplied and summed, is a sample output of twice the amplitude as the input sample. What happens on the "f" component after multiplication and summation, which is only 180° along at the 50th sample, is a net result of zero. Thus the "2f" frequency is passed and the "f" component is cancelled.

From the previous discussion a general equation of a nonrecursive filter may be derived:

$$y_s = \sum_{n=o}^{M} X_n w_{s-n}$$

where w_s = input signal
X_n = constants that determine the filter characteristics
y_s = output signal

This is a very simple explanation of how a nonrecursive filter works. A recursive filter was considered, but its non-linear phase characteristics, plus its tendency toward possible unstable states created by the output samples being fed back to the input, discouraged its use in this application.

Sampled analog switched-capacitor filters were also evaluated but rejected because the bandwidth is not under program control and exhibits a poor shape factor for this application, because they are not phase linear, and because they are burn-out sensitive when power is lost.

With this understanding of digital filtering, it can be seen that it takes multiple cycles of data to fill the delay blocks. The number of cycles depends upon how many delay blocks are in the filter. In the example of 50 samples per data cycle, if 500 delay blocks were implemented, the filter would contain ten cycles of data during processing. This results in excellent transient response and slew rate characteristics which also enhance data reliability.

Tach Signal Conditioning

In an aircraft turbine engine the vibration component that determines the engine's health is the component tied to the fan or rotor speeds. All other signal sources (accessory vibration, cable noise, etc.) are not of interest in determining engine health. The digital narrowband filter is therefore tied to the engine's tachometer signal which then provides a synchronous output signal, free from noise, that can be further processed or presented to the flight deck for display.

The tachometer input signal is conditioned and presented to a microcomputer-based tach ratio generator where ratio calculations are made. Ratio changes, necessary due to different engine types, are easily programmed on the ATR box connector. In this way many ratios may be stored in the microcomputer's ROM memory and easily selected by a wire jumper on the mating connector of the ATR box. The output of the microcomputer in the ratio generator is used to clock the digital narrowband filter. In this way the center frequency of the filter is synchronous to the fan or turbine speed of the engine.

Ouput Signal Conditioning

The output of the digital filter is fed into a digital-to-analog converter to reconstruct the signal of interest for display. A standard analog meter display will be maintained in the cockpit. An RMS to DC converter converts the sinewave output of the D/A to a DC signal proportional to the RMS value to drive the meter display. The RMS value is then sampled and fed back on the microcomputer bus for further processing. This feature adds the capability of combining signals for display or recording.

ADDITIONAL ADVANTAGES OF A DIGITAL SYSTEM

By implementing a digital filter and tach ratio generator the system is given computational power that is only partially used in the filter and tach ratio implementation. The computing time remaining can be used to provide additional features to meet the expectations of an on-board engine vibration monitoring system.

Better Discrimination Against System Malfunction

Self-test and signal integrity test functions have been implemented in the software of the microcomputer. The signal integrity check is performed automatically every 0.5 seconds as a check of the input signal's integrity. If the integrity check fails, the signal to the cockpit is shut off and a system-fail signal displayed. At this point the flight engineer may initiate a self-test function that starts an internal diagnostic check of the entire digital system. If this self-test determines that the digital system is functioning properly it is deduced that a bad transducer, connector, or cable is generating an unacceptable signal. If the self-test fails, the electronic box has failed. This type of failure isolation will assist maintenance in taking action to clear a system "squawk".

In-Flight Balancing

With a computer system on-board it becomes feasible to perform calculations on the vibration data to assist maintenance in balancing and to gather data that will permit finer balance. This should eliminate the need for multiple ground run-ups, which will save man-hours, conserve fuel, and should extend accessory and engine life.

Amplitude data at cruise is made available to the microcomputer. If a once-per-revolution pulse is presented to the microcomputer on the tach input signal, a phase reference can be calculated. With phase reference and amplitude information available, the microcomputer consults a look-up table to pick the weight and mounting position for the weight to balance the engine. The look-up table can be changed for various engine types. The resulting information is stored in memory and may be read out by connecting a very simple readout device on the output connector of the system.

Data Base on Individual Engines

With the data available in digital form, further calculations may be performed to assist maintenance in tracking engine health. One useful parameter is events above threshold. If the amplitude of the vibration exceeds a pre-set threshold level it would be useful to record the event, to record the RPM, and to record the time of occurrence. The present system performs this task easily by storing in memory a threshold level for every 3% increment in RPM. The microcomputer reads the RPM value, pulls the proper threshold level from its memory, and compares the incoming data amplitude. If the threshold is exceeded, it counts the event and stores the time and RPM. This function is performed in a 2nd 1/4 ATR box that contains sufficient nonvolatile memory to perform this and other functions.

Trend Analysis

Trend analysis is performed by calculating a moving average of the vibration amplitude for every 3% increment in RPM. This is done in the 2nd 1/4 ATR box containing the non-volatile memory.

CONCLUSION

To meet the expectations of an airborne vibration monitoring system it has been deduced that the system must contain digital narrow-band filtering to obtain the stopband characteristics required, must perform signal integrity checks and internal system diagnostic checks to assure a properly functioning system, and must store sufficient data to permit proper engine vibration diagnostics to meet on-condition maintenance requirements. The Series 6670 system just described combines the latest digital technology and information available from aircraft engine monitoring systems now in operation, to produce a system that meets these expectations.