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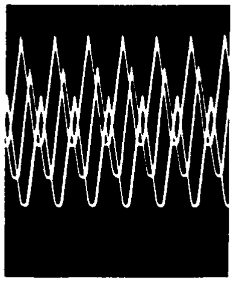

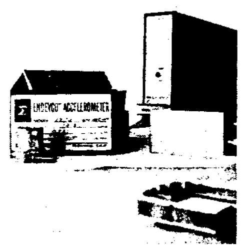

TP 285

MODERN TECHNOLOGY AND AIRBORNE ENGINE VIBRATION MONITORING SYSTEMS

D.J. Ray, Advanced Systems Manager, ENDEVCO
and
R.L. Kallio, Principle Engineer 757 Propulsion Project
Boeing Commercial Airplane Company

ABSTRACT

The vibration data from turbine engines used as aircraft power plants has long been recognized as an important parameter to measure in test cells. However, the same measurement taken while the aircraft is in flight has had only mixed and sometimes marginal success. The knowledge base on how to reliably make such measurements has steadily increased over the years. This paper describes an improved method of processing vibration signals inflight. This technique has demonstrated that if properly implemented, it can provide aircraft operators and flight crews with reliable and accurate engine rotor imbalance information about their aircraft.

REVIEW OF GOOD PRACTICE IN VIBRATION MEASUREMENT

The inherent limitations and short life span of the velocity coil has resulted in the modern practice of using piezoelectric (PE) accelerometers for airborne vibration monitoring AVM) systems. The velocity coil contains a moving internal shuttle held in place by springs. It is therefore orientation sensitive and prone to wear. The PE accelerometer on the other hand contains no moving parts to cause wear and is not orientation sensitive. However, the PE accelerometer has a high impedance output. Despite this high impedance nature of the PE transducer, which sometimes manifests itself in high electrical noise levels, the advantages over the velocity coil are such that it is now widely recognized that PE accelerometers are superior sensors. In order to benefit from these advantages good implementation technique must be used. Some of the techniques are diagramed in Figure 1 and listed here:

- PE accelerometer outputs should be differential and processed by differential charge amplifiers.
- Low capacitance ($C_{1,2} < 10$pf) should be maintained from the accelerometer case to its signal leads.
- Very small capacitance differences ($|C_1 - C_2| < 2$pf) should be maintained between each signal lead to the accelerometer case.
- Aircraft cable carrying charge signals should be low noise twisted pair and shielded.
- Cable should not be allowed to vibrate against other surfaces.
- Connectors should be kept to a minimum and free of contamination.
- Connectors should be kept tightly mated and individual pins must not be allowed to rattle.
- The cable shield should be continuous for the entire length of the cable and connected to the signal common of the differential charge amplifier at the signal conditioner.
- The cable shield should maintain high isolation (both resistive and capacitive) from the accelerometer case and airframe at the accelerometer end of the cable.
- The signal conditioner common should be single point grounded to the aircraft frame as close as possible to the signal conditioner.
- A separate bonding strap (or second shield) should be placed between the accelerometer case (or bracket) and the signal conditioner grounding point.

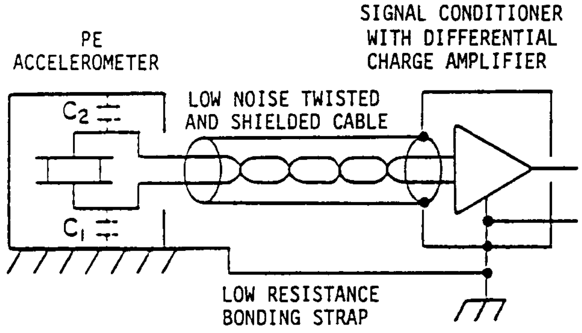

Figure 1. Grounding and Shielding for Differential Charge Systems

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Despite the above precautions higher than acceptable electrical noise may still be encountered. In addition, vibration components unrelated to rotor imbalance may obfuscate the synchronous signals of interest. While this discussion places emphasis on the synchronous vibrations of the engine rotors, in order to detect rotor imbalance, the AVM system described also monitors and displays the rms value of the broad velocity vibration spectrum. If electrical interference is present and it is not periodic but appears as "spikes" which occur randomly in time the noise spectrum in the acceleration signal looks approximately as in Figure 2. These "spikes" may be the result of problems in the accelerometer, the connectors, or the cable. If this noise is then integrated using standard analog techniques the velocity spectrum appears as Figure 3. The small residual noise levels at the high and low ends of the spectrum result from the electronic components in the integrator. The charge amplifier and integrator low frequency cut-off characteristics contribute to the steeper roll-off on the low frequency end. From Figure 3 it is clear that the propensity for the integrator to greatly amplify signals in the 10 Hz to 30 Hz range (in this example) means that any significant noise components in this region spell trouble for accurate vibration measurements using traditional wideband techniques.

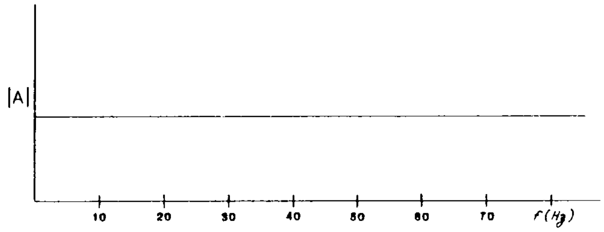

Figure 2. Noise Spectrum at Input to Charge Amplifier

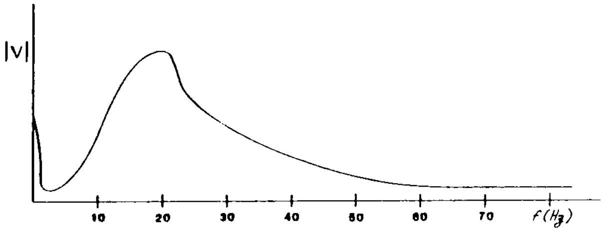

Figure 3. Noise Spectrum Out of Integrator

Improvements in active analog filters and the fact that the angular speed ranges of the different rotors of turbine engines may only slightly overlap have resulted in AVM systems using multiple fixed bandpass filters with a separate filter designed for each rotor. This again results in some reductions of the noise level but not to the extent needed for accurate measurements.

DIGITAL SIGNAL PROCESSING - AN INNOVATION

A significant improvement was made with the introduction of the digital tracking filter. In 1979, advances in digital signal processing and microprocessor technology had reached the point that their applications to the field of vibration measurement and more specifically to inflight vibration measurements were obvious to Endevco. This, coupled with Endevco's previous experience in accelerometers and airborne vibration monitoring, presented the opportunity for a major advance in inflight measurements. At that point the Model 6670 series of Digital Tracking Filters for airborne use was conceived under the trade name of MICROTRAC. By using digital techniques the filter characteristics could be made to approximate the ideal filter shape. Also, by making the filter digital, a narrowband filter could easily be made to track the rotor speed under the control of a microcomputer provided the tachometer signals were also available. Figure 4 compares the narrowband digital tracking filter response at three N1 frequencies with a fixed frequency broadband analog filter response on the same plot.

Such digital filters have the capability of eliminating the greatest part of the noise while preserving a short transient settling time. By using the clocking rate to vary the center frequency of a digital filter, the filter will retain the same Q (the ratio of center frequency to bandwidth). That is, while tracking the rotor frequency, the relationship between the filter center frequency and bandwidth will remain the same. If a previous stage has integrated the signal then constant Q is a distinct advantage in a tracking filter. This is obvious from Figures 3 and 4 since with constant Q the bandwidth in the lower operating speed range becomes very small. Consequently the bandwidth is narrowest in the region of greatest noise.

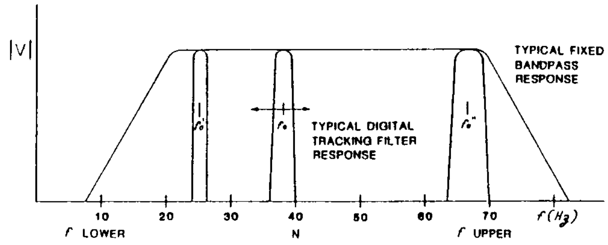

Figure 4. Comparison of Typical Digital Tracking Filter Response to Typical Fixed Analog Response

As development of the digital tracking filter neared completion it was offered for commercial use. The Boeing Commercial Airplane Company evaluated and accepted it as standard equipment for both their new Rolls Royce and Pratt and Whitney powered 757 aircraft. At about the same time, Boeing offered it as optional equipment on their GE powered 747 and later on their GE powered 767 aircraft. The MICROTRAC digital signal conditoner is now qualified and certified for these aircraft.

The actual embodiment of the innovations previously described and incorporated in MICROTRAC is shown in Figure 5. The exceptional flexibility of the device is also now apparent. By modifications to the resident software, the MICROTRAC can be programmed to accomodate up to eight independent channels of tachometer data. Also, the different tachometer frequencies of different engine types are programmable. By modification to software the acceleration data accommodated may come from co-located sensors or from sensors in different locations on the engine.

In Figure 5 notice that each acceleration channel has its own separate charge amplifier and integrator and that the broadband acceleration is made available at the rear panel connector for engine maintenance purposes. Two broadband filters process the velocity data which are subsequently converted to digital form and dispatched to the microprocessor. The digital filters are of the non-recursive type. This type of digital filter is guaranteed stable since it uses no feedback loops. The filters in the signal conditioner described here are made with hardwire digital logic with clock frequency controlled by the microprocessor. Since the center frequencies of the digital filters are dependent on the clock frequencies, a change in clock frequency causes a change in the filter frequencies. This results in two constant Q variable frequency bandpass filters which process two channels of data simultaneously. The filters are then multiplexed through the other channels two at a time.

Each tachometer channel also has its own separate conditioner. These inputs are resistively protected with 200 Kohms to prevent the tachometer line from experiencing a low impedance fault should a failure occur in the unit. Tachometer lines may be either single-ended or differential which are converted to a digital format and forwarded to the microprocessor.

The MICROTRAC concept is built around the nucleus of the microprocessor. Additionally, this device serves a multitude of secondary objectives such as self test, BITE, data formatting, data verification, and alarm level triggering.

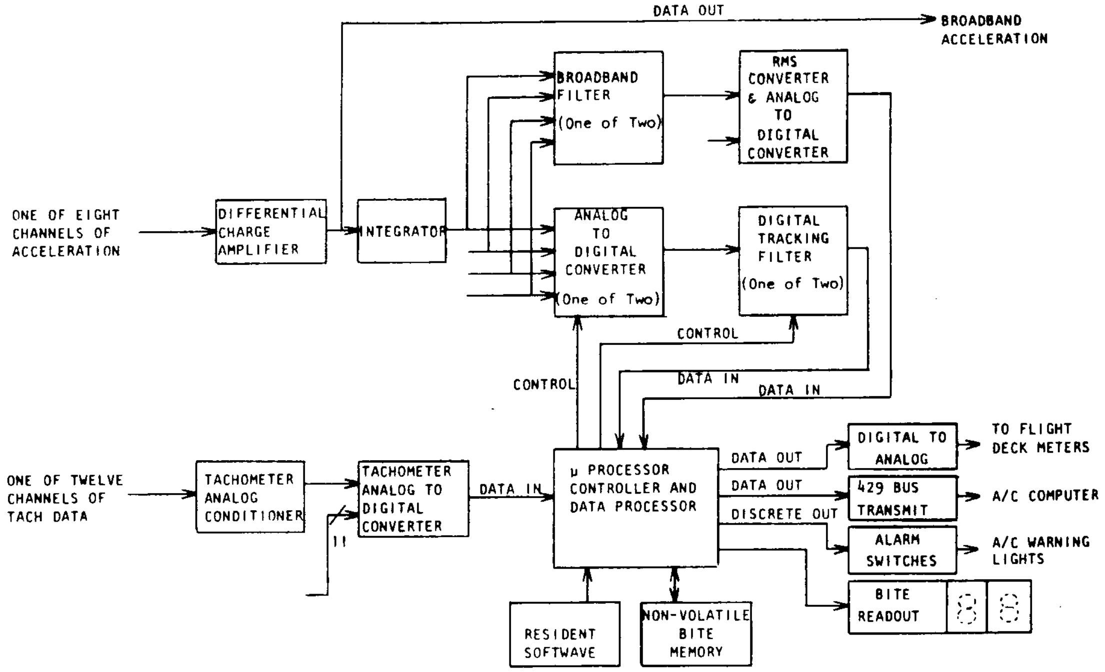

Figure 5. Simplified MICROTRAC Block Diagram

The number of tachometer pulses for each rotor revolution must be converted to the number of data samples per rotor revolution. This is done to ensure that the A/D converter for the vibration data converts the correct number of samples per cycle which in turn causes the digital filter to track the rotor. This conversion is done by the microprocessor with the proper conversion factor stored in resident software. The same factor is used by the microprocessor to center the digital tracking filter at a frequency corresponding to the rotor frequency.

The microprocessor receives the digitized data from both the broadband filter (via the rms and A/D converter) and from the digital tracking filter. The microprocessor then scales the data to its peak value and performs a data validity check by comparing the amount of noise present in the broadband signal with the spectral components from the tracking filter. If the noise level is very high and the tracked signal levels are very low the channel is declared as faulted and that fact is stored in non-volatile memory. The microprocessor also compares the vibration levels to the preprogrammed alarm levels and sets the alarm switches accordingly, thus providing the flight deck with a caution indication.

The data are formatted by the microprocessor and routed to the digital to analog converter and 429 bus transmitter. The signal conditioner is therefore capable of providing outputs to aircraft whose flight decks use either analog meters or 429 bus receivers and cathode ray tube displays, or both.

MICROTRAC contains extensive programming to detect AVM system faults. This is the Built In Test Equipment (BITE) feature. This feature, as mentioned earlier, constantly checks the data for dynamic faults in the forward system (accelerometer and cable) by comparing the signal and noise levels. Resident software also contains modules which result in constant monitoring of the tachometer signals and alerts BITE to loss of tachometer data. Such BITE data is stored in nonvolatile memory for later recall. BITE data is displayed in two hexadecimal readouts on the front panel. A plate on the front panel explains the BITE codes. The non-volatile memory will retain BITE data for up to one year with power off under normal temperature conditions.

INSTALLATION AND OPERATIONAL EXPERIENCE

Boeing has chosen to install the MICROTRAC signal conditioner in the electronics bay of the 757 aircraft. It is connected to the engine accelerometers utilizing low noise twisted pair and shielded wires installed in the manner recommended earlier. The MICROTRAC output is provided in digital form per ARINC standards to the Engine Indication and Crew Alerting System (EICAS) computers. Appropriate switching of the pilot's display select panel will present AVM along with other secondary engine parameters on the EICAS cathode ray tube display unit. Figure 6 shows the arrangement of the system while Figures 7 and 8 show the flight deck display.

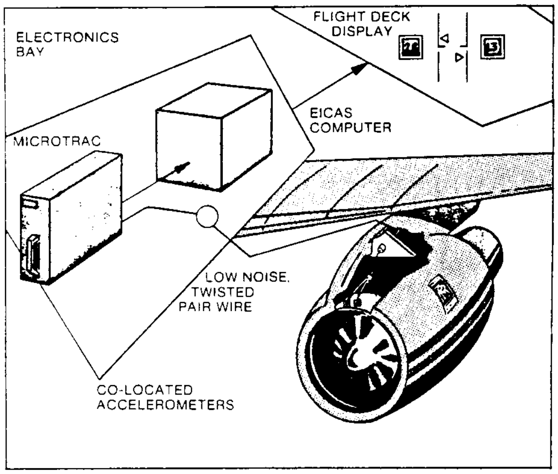

Figure 6. Aircraft Schematic

Boeing 757 aircraft have undergone approximately 2 000 flight test hours during the certification process which included many types of specific testing intended to exercise the aircraft systems and airframe. Several airlines, both domestic and foreign, have now entered the 757 into service. The AVM system has performed as intended throughout testing and in service flights continuously monitoring the state of engine health.

One specific category of certification testing involved aircraft/engine icing demonstrations. The AVM system was utilized to observe changes in engine vibration as ice accumulation was allowed to build-up and was subsequently shed. The flight crew was able to observe the vibration increase and to make the engine operational clearing actions to remove ice and reduce vibration.

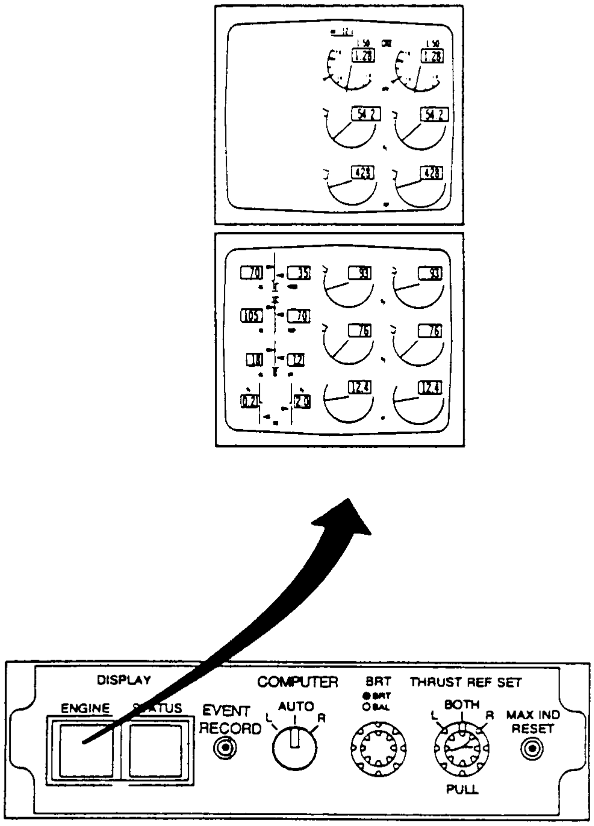

Figure 7. Pilot's Display Select Panel

The AVM system as installed has provided sufficient accuracy and resolution to accomplish on-wing fan trim balance needs arising from engine component changes or bird strike incidents.

A specially instrumented 757 aircraft was utilized to obtain engine in-flight vibration data which was later compared to the engine manufacturer's test cell vibration baseline data. The results of this comparison showed that the engine vibration levels, measured and processed by the aircraft AVM system, correlate directly with the engine manufacturer's test cell vibration signature within normal data scatter and without any need for a correction factor.

CONCLUSION

Over the years the techniques and practices of sensing, shielding and signal conditioning engine vibration data using piezoelectric accelerometers have improved significantly. These techniques may now be coupled with digital signal processing using microcomputers to control, analyze and validate the data before presentation to the flight deck. The results of combining this knowledge have dramatically improved airborne vibration monitoring systems by providing reliable, accurate, and meaningful data to flight and maintenance crews as well as reduced costs for aircraft operators. These new systems are just entering service. As additional flight experience accumulates, there is every reason to believe that the previous reputation of airborne vibration monitoring systems will give way to a new, significantly improved level of AVM credibility.

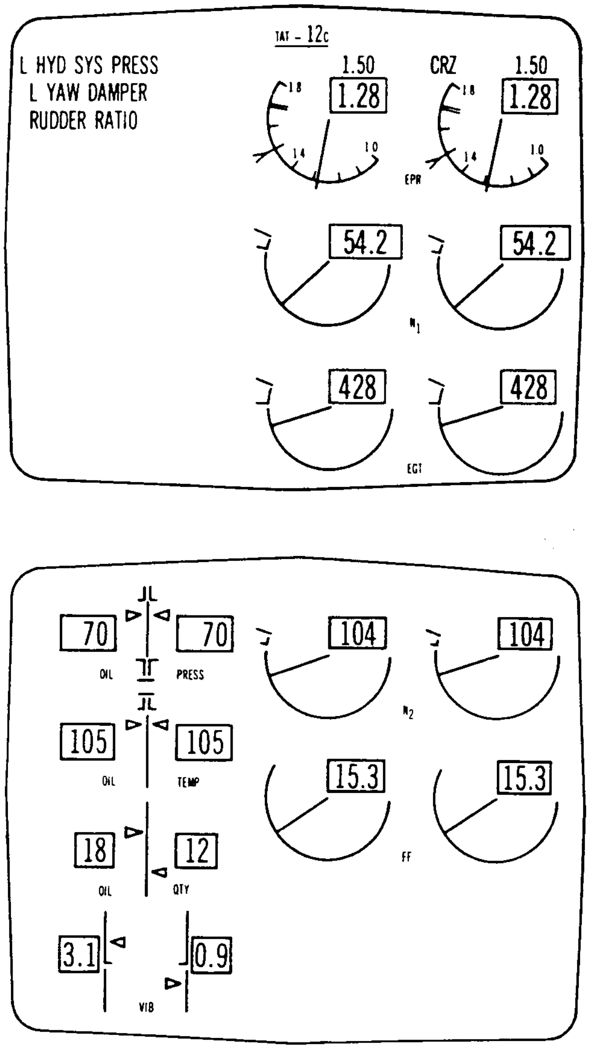

Figure 8. EICAS Display