QUALIFYING THE COCKPIT VOICE RECORDER AS AN INSTRUMENTATION RECORDER AND AIRCRAFT STRUCTURAL MONITORING INSTRUMENT

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ABSTRACT

A novel concept using the cockpit voice recorder (CVR) as a structural vibration recording device, to aid in structural health monitoring of commercial and military aircraft, is outlined. The unused cables in the CVR wiring harness act as “latent transducers” that respond to structural vibrations, generating vibration signals, which the CVR records. Postprocessing of such data can provide clues to problem areas or changes in the signature of the aircraft. The standards which the CVR must meet to qualify as a instrumentation-quality recorder are discussed and the steps required to assure compliance are outlined.

KEY WORDS

Aircraft structural monitoring, triboelectric effect, instrumentation recording, structural acoustics, IRIG Standards

INTRODUCTION

The maintenance monitoring and structural integrity of airplanes has attracted greater attention as the average age of both military and commercial aircraft has increased. Thus, concerns about structural soundness and finding economical methods to diagnose structural problems have increased.

Although the first documented problem with structural integrity is said to have occurred in 1903 when the Wright brothers suffered a cracked wooden propeller, for many years the rapid evolution of new aircraft designs and the quick obsolescence of older designs meant there was not a premium on aircraft longevity. An aircraft was usually retired long before its design lifetime was reached. [1] More recently, tight budgets and profit margins have resulted in aircraft being used beyond their initial prescribed lifetimes. Concern about preserving safety with increased airframe hours, and the maintenance and inspection hours required to do so, is a major emphasis in today's aviation community. If an existing aircraft instrumentation system can be extended to function as a structural health monitoring aid, further savings in both equipment cost and time can be gained. The rotary wing community has already recognized this and is implementing health and usage monitoring systems (HUMS).[2,3] HUMS are adapting flight data recorders to monitor for adverse vibration or other pending failure indications. The military is developing hardware systems to analyze the recorded signals from the flight data recorders using commercial off-the-shelf (COTS) technology. Reuse of existing data recording assets which currently are found in many aircraft, such as cockpit voice recorders (CVRs), would be an extension of this philosophy.

STRUCTURAL MONITORING

Recent advances in aircraft crash investigation techniques have shown that the CVR or the flight data recorder (FDR) could fulfill an added role of aircraft structural health monitoring.[4] Modeling and prediction of various failure modes of an airframe design are possible, making signature identification more focused.[5] The acoustic spikes in the time series of Figure 1 are attributed to a broken engine mounting from an aircraft CVR track and were recorded long before the aircraft crashed. Study of failure reports that detail part failure over the aircraft lifetime can provide insight as to which failure-prone parts should be modeled and monitored. Structural modeling of those parts and their impact on the overall structural response can provide predicted acoustic responses prior to failure.

The predicted acoustic response can then be used to focus the analysis of the CVR data. In the crash case study of Reference 4, after expected failure acoustic frequencies were identified for the suspected failing structures, the surviving cockpit voice recording was examined for appearance of those acoustic signatures on the three microphone-equipped channels. FM modulation characteristic of whirl flutter vibration was found on a warning horn tone recorded on the cockpit area microphone (CAM) channel as shown in Figure 2. In addition to the three microphone-equipped channels, this standard analog CVR, like those on many commercial aircraft today, had a fourth channel that had been provided for the voice of a flight engineer. The standard instrumentation recorder analysis technique of magnetic image development of the tape, using Edivue or Magnesee magnetic powder in a solvent, revealed that all four tracks contained recorded signals. At the end of the recording, a high amplitude signal was found on all four channels as the CVR shut down upon loss of dc power. This occurred in spite of having only three microphones connected to the recorder!

The existence of recorded signals on the tape track which was not connected to a microphone raised the question of whether the fourth track recorded signals throughout the flight, without the background noise of cockpit microphones. Further study of this fourth, under-recorded track, revealed significant structural acoustics information, even landing gear touch-down sounds, clearly audible on enhanced replay of the master tape.

Examination of aircraft wiring practices for use of CVRs, FDRs, and other applications revealed unused wires that are often pulled in harnesses to facilitate later wire repair or the installation of additional instrumentation. This discovery led to speculation that signals reached the fourth track through a process called latent transduction in the existing unused microphone cable connected to the recorder. Aircraft structural vibrations produced voltages on this cable by means of the frictional process of the insulation sliding on the wire, known as the triboelectric effect. [6] The triboelectric effect between wire and insulation is shown in Figure 3.

Detailed searches for other sources such as coupled electrical fields were conducted prior to reaching the conclusion that the recorded signals were due to triboelectric effect. The voltages from this latent transduction were related to identifiable engine and structure vibration, such as the wheels hitting the runway. Later laboratory testing on an aircraft using ground vibration tests (GVT) confirmed that various types of aircraft wiring readily transduce vibration by means of the triboelectric effect and thus act as microphones. [7,8] For example, in Figure 4, the vibration signal obtained with a pair of wires taped to the airframe of an aircraft with its engine running is shown. Several tonals below 625 Hz appear to be related to blade passage rate. The other prominent line in Figure 4 shifts in frequency with aircraft engine rpm.

In contrast with the vibration acoustic signals, recorded electromagnetic interference events, if they show up as (demodulated) spikes at all, will have a much sharper, singular oscillation and can be readily distinguished from true vibration-related events. For example, an electromagnetic signal has been studied using triboelectric wiring pickup from an electronic aircraft-type strobe light placed next to the wiring. [7] The signal amplitude from a strobe falls off quickly with increasing distance from the wire and is clearly distinguished from acoustic spikes of vibration sources. The case study discussed in Reference 4 also explored the possible existence of electromagnetic spikes on the CVR recording from demodulated radar “hits,” but none could be correlated with the known radar time lines during the recorded flight time.

The analysis for the crash case study also showed two sources of vibration were recorded by the CVR before catastrophic failure: the CAM channel contributed major evidence of whirl flutter failure, while the fourth track contained triboelectric acoustic spike signatures at the frequency predicted by the acoustic model of a broken engine mount. If this much evidence of impending failure was being recorded before a crash, then a periodic inspection of CVR tapes might have revealed changes from a reference recording signature of the aircraft taken under new and normal operation conditions.

RECORDER CONSIDERATIONS

Can a recorder that was originally envisioned as recording only voices during flight be relied upon to produce instrumentation-recorder-quality information? The mechanical and thermal construction of these recorders is enhanced to survive crash forces and any fire and heat, aiding in reliable functioning and quality recording during turbulent flight or in the event of a crash. This rugged design contributes to the recorder's instrumentation quality performance.

In Reference 4, standard telemetry lab methods were used with the CVR master tape and copies as specified by the standards of the Inter Range Instrumentation Group (IRIG). [9] These aerospace test-range standards for recorder checkout and calibration were used to calibrate the data from latent transduction. An instrumentation recorder must be checked for at least: 1) speed accuracy and stability, 2) frequency and amplitude response, and 3) tape saturation and distortion. Only then can the recorded data be interpreted accurately. Outside influences on the tape speed, which appear as an FM modulation of stable recorded tones, are known as flutter. To use structural signal analysis, the recorder mounting and tape path should be designed so that flutter is low and can be measured to IRIG standards. Even if a known motor speed flutter exists, it can be minimized in the data analysis using a fast Fourier transform (FFT) acoustic analyzer. In addition to the FFT, time series and waterfall type spectrum displays add to the utility of such an instrument when used to analyze an aircraft recorder tape. Structural signal analysis can proceed using calibration techniques taken from the IRIG standards. Let us consider the three calibration issues listed above and how to measure them to IRIG standards using the recorded CVR signals and standard test tapes.

I. SPEED SPECIFICATION:

The CVR has a tachometer-based, constant speed motor reference control. Thus, speed can be inferred by measuring known frequencies recorded anywhere on the tape. It is possible that outside-induced motor flutter can exist from crash forces, or from turbulence. But the CVR is shock mounted on vibration mounts which typically attenuate flutter band frequencies by at least 20 dB, or a reduction of 10 times in terms of voltage. This attenuation has proved sufficient to isolate the motor speed from outside forces in accident studies. Thus, constant speed recording of constant frequencies is virtually assured.

II. AMPLITUDE AND FREQUENCY ISSUES:

Much of the information that is useful for failure prediction in machinery monitoring comes from fundamental and harmonic frequency behavior of rotating components such as bearings. *Absolute* amplitude is not as important as *relative* changes in amplitude and harmonics compared to past historical records. The analog CVR can record to over 10 kHz at its 1 and 7/8 ips tape speed. In the case study, [4] the CVR recorded the fundamental revolutions per minute (RPM) and harmonics of turbines and associated gear boxes. These spectral features were particularly clear on the latent transduction track as there is no cockpit acoustical noise to mask lines. A quite adequate relative amplitude calibration of each CVR channel can be provided, as in IRIG practice, by industry-standard audio amplitude and frequencies test tapes. [10] In the Reference 4 case study, these tones were used to verify the playback equipment amplitude calibration, provide a relative reference amplitude for the master tape, and provide standard frequencies for comparison to vibration frequencies.

Occasionally during analysis, tape oxide or lubricant deposits can reduce the signal amplitude recorded on a particular channel if the lubricant or oxide is deposited over the channel path on the tape. The reason for the signal amplitude reduction can be readily determined through measurements made using an optical microscope to locate the spot of extra thickness on the tape. Wallace's formula for the amplitude reduction caused by debris on the tape states that the voltage amplitude loss, in decibels, is equal to 55 times the thickness of the debris, divided by the wavelength ( ) of the signal frequency. [11] If the amplitude reduction follows this formula, it is caused by oxide or lubricant deposits, rather than another mechanism.

III. TAPE SATURATION AND DISTORTION DETERMINATION:

In the sudden shutdown of a dc-powered CVR, there are also excellent test signals provided by the erase head and record head shutdown signatures that reach the saturation magnetization of the tape, and are, by definition, the highest amplitude that can be recorded in the magnetic medium. For use as an absolute maximum amplitude measurement reference, these transients must not be clipped in copies of the master tape, which will be used as working copies in analysis. The shutdown transients are one source of a saturation test for the third point of the calibration considerations. Normal shutdown of the recorder may not produce transient saturation, depending on the particular recorder design and power method. Distortion of any recorded signal can be compared to tape recorder standards defining harmonic distortion levels for second and third harmonics. Many higher harmonics appearing in the spectrum indicate saturation of recorded data signals and can be used as a saturation test as well. If excessive distortion or saturation is detected on recorded data signals, the signals may be used for fundamental frequency analysis but cannot be used reliably for amplitude analysis.

The analog CVR in performance resembles an IRIG intermediate band instrumentation recorder, having fixed azimuth heads for its endless loop cassette. Thus, azimuth effects are controlled by the recorder design and the short, closed-loop tape path. Well-documented IRIG instrumentation tape recordings should include a pre- or post-amble sequence of frequency and amplitude calibration signals used for azimuth checks and amplifier equalization over the frequency band. The CVR does not itself provide such a calibration sequence, but in normal operations of flight, it usually records very good signals for frequency calibration use. These signals are of several forms, including any nondirectional beacon (NDB) or VHF omnidirectional range (VOR) identification signals, which have Morse Code tones that record periodically on the recorder radio channel. The Morse Code identification (ID) tones are very accurate and are periodically calibrated by the Federal Aviation Administration (FAA).

Other sources of frequency calibration signals, for comparison to vibration signature frequencies, are the various warning horns that are recorded by the cockpit area microphone (CAM) channel. The warning horns are recorded when the aircraft leaves an altitude or approaches landing, and the pilot is reminded by audible warnings to lower the landing gear or perform other critical tasks. These tones are sounded in stable, repeated sequences and have been used in the case studies cited.

Real-time spectral analysis with acoustic FFT analyzers can be used on the CVR tape signals to verify the various calibration tones and, thereby the speed accuracy of the individual recorder, since the recorded tone will differ from the expected frequency if there is any speed error in the recording. The FFT analyzer also can yield a measurement of any recorder flutter on these same tones. Flutter appears as high amplitude sidebands about a single tone. Any change in flutter would appear as an increase in the upper and lower sideband amplitudes about a given tone, with certain sideband threshold amplitudes representing acceptable flutter levels. Large sideband levels indicate unacceptable flutter levels and may be useful in parts failure identification.

Using FFT real-time analysis, the frequency of a specific warning horn early in a tape and its frequency during a later warning during which vibration is being experienced can be measured and compared. Vibration will modulate the tone in both amplitude and frequency. Modulation and harmonic analysis, with the study of the slope of harmonic amplitude decay, dramatically shows up as vibration modulation of otherwise steady tones. The vibration modulation will produce modulation peaks spaced by the frequency of the vibration.

The continuous playback of a CVR tape into a type of real-time spectrum analyzer waterfall display, such as a color spectragram, gives a dynamic picture of a flight, and of the changing of power train RPM and airframe vibration with airplane speed and maneuvers. Many other methods of analysis of the data are available, but are beyond the scope of this paper and will be presented in other publications.

UTILIZING STRUCTURAL VIBRATION RECORDINGS

The cockpit voice recorder, then, can be certified by the methods of the IRIG recorder standards to function as a special purpose telemetry recorder of aircraft structural information on both conventional microphone channels and those unused channels whose wiring can support triboelectric effects. A quick look at such a tape is most easily accomplished with a color spectragram from a real-time FFT acoustic analyzer, but time series data and frequency spectra can also be used to better understand vibration-induced signals that have been recorded during flight. These signals can be compared to the vibration data history for that particular airframe as recorded in previous flights to identify potential parts failures. The data can also be compared to acoustic models of known failure-prone components. It is the coupling of the recorded information available from each flight with computerized real-time spectrum analyzers and structural failure modeling that may offer a superior acoustics-based methodology for structural vibration monitoring.

CVRs of the analog type will be used for some time in many existing commuter and short-haul aircraft such as the Boeing 737. Over 40,000 CVRs made by just one manufacturer, L3 Flight Recorders (formerly Fairchild), have been installed, and most are still in service.[12] The commuter fleet, which needs better maintenance monitoring, is primarily equipped with such recorders. The methods discussed here are also applicable to the newer digital recorders and the new combined voice and flight data recorders. Such recorders are found on all larger aircraft and increasingly on military aircraft, especially of the rotary wing type.[2,3]

CONCLUSION

Today, when significant emphasis is being placed on using commercial off-the-shelf (COTS) technology on government and other projects, it seems prudent to explore the capabilities of existing equipment as well for use with computerized spectrum measurement for in situ maintenance monitoring tasks. Unlike new COTS technology, CVRs and FDRs are in place and operating today. Using the methods outlined in this paper, the CVR can be calibrated by standard instrumentation recorder techniques. Coupled with a proactive study of repair history to predict what signatures might be recorded and should be tracked, the CVR/FDR offers a continuing and efficient way to monitor aircraft structural health.

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REFERENCES

1. Griffin, Kenneth E., Principal Engineer, Aerospace and Reliability Engineering Department, Materials and Structures Division, Southwest Research Institute. Lecture to AIAA section meeting, San Antonio, Texas, 27 February 1998, at Southwest Research Institute.

2. Smith's Industries World Wide Web site, <http://www.smithsind-aerospace.com>, Health and Usage Monitoring System.

3. Altair World Wide Web site, <http://www.altair.rotor.com/hums1022.htm>, Health and Usage Monitoring System.

4. Stearman, Ronald O., Glen H. Schulze, Stuart M. Rohre, and Monte C. Buschow, "Aircraft Damage Detection from Acoustic and Noise Impressed Signals Found by a Cockpit Voice Recorder," Proceedings of Noise-Con 97, The Institute of Noise Control Engineering, Pennsylvania State University, State College, Pennsylvania, 17 June 1997.

5. Cohen, Phillip, "Failing Airframe Speaks Volumes to Engineers," <u>New Scientist</u>, London, 28 June 1997, p. 6.

6. "Triboelectric Effects," <u>LOW LEVEL MEASUREMENTS</u>, 4th Edition, Keithley Corp., Cleveland, Ohio, 1993), Section 3, pp. 33-34.

7. Kantor, Andrew; and Dallen Reese, "Drak Corp., ASE 363Q Final Report," The University of Texas, Austin, Texas, December 1997.

8. Budinszky, Andras, Edward Lopategui, and David McDonald, "MBL Aerospace, ASE 363Q Final Report," The University of Texas, Austin, Texas, May 1998.

9. Inter Range Instrumentation Group (IRIG), "Test Methods for Telemetry Systems," document 118-79, Range Commanders Council, White Sands Missile Range, New Mexico, 1979.

10. Technical Data, Calibration Tape 19-6 IEC 2/ANSI, BASF Magnetics, GmbH., Mannheim, Germany.

11. Jorgenson, Finn, <u>THE COMPLETE HANDBOOK OF MAGNETIC RECORDING</u>, Tab Books 1059, 1980, p. 82.

12. L-3 Communications Corporation Aviation Recorders World Wide Web site, <http://www.l-3ar.com>.

Figure 1 O.86 Hz spikes from broken engine mount tube ends

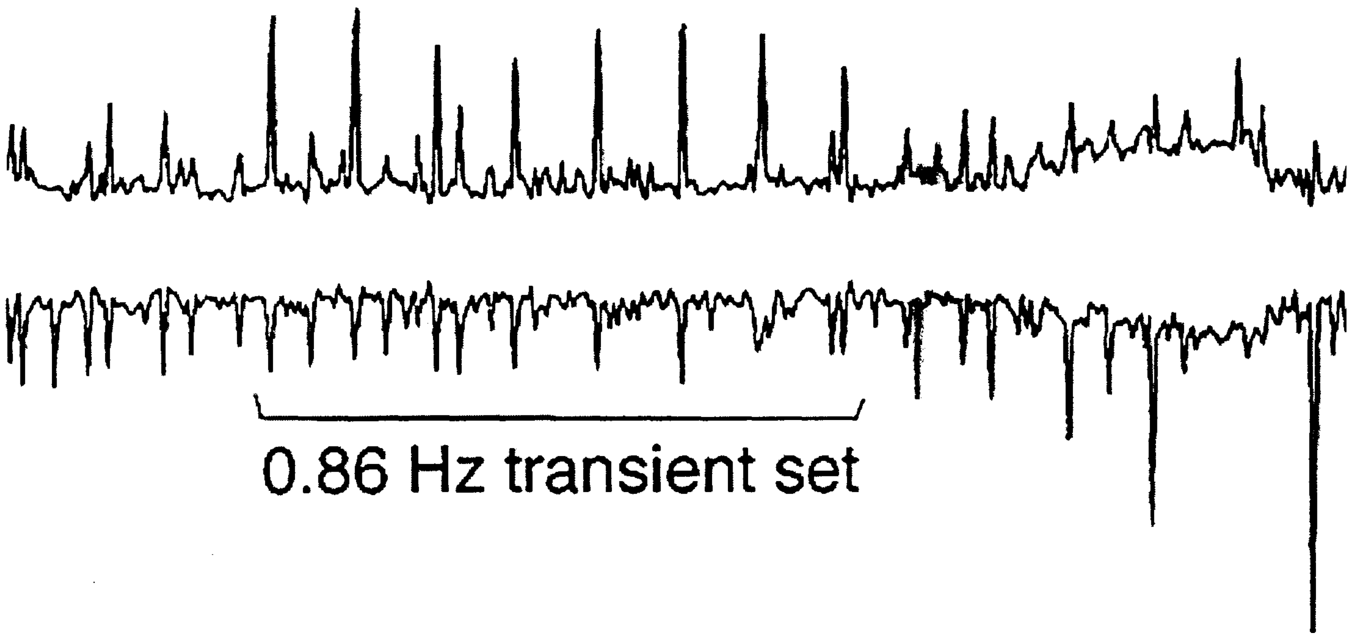

Figure 2 Whirl Flutter Modulation of a Warning Horn

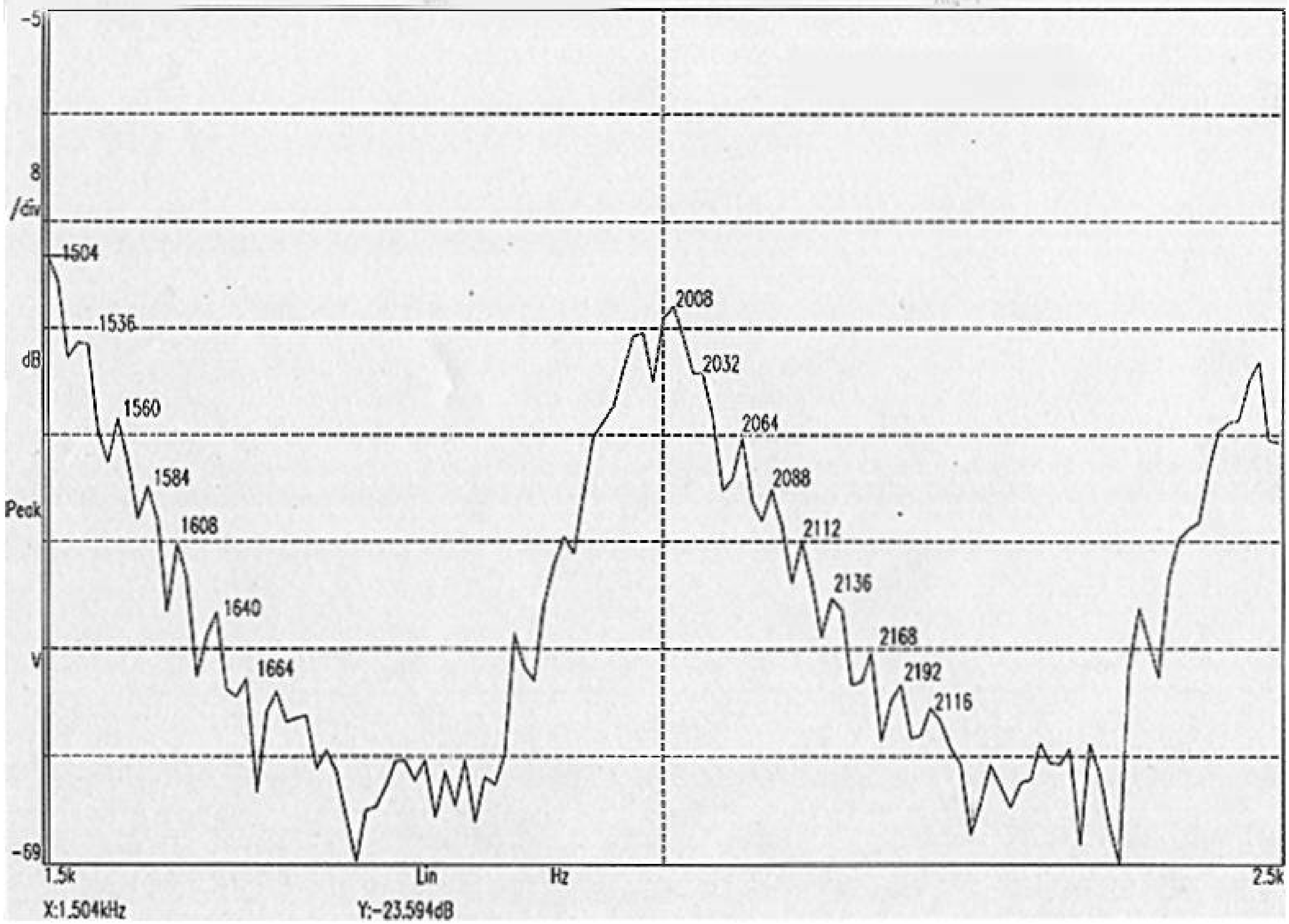

Figure 3 The triboelectric effect in wiring

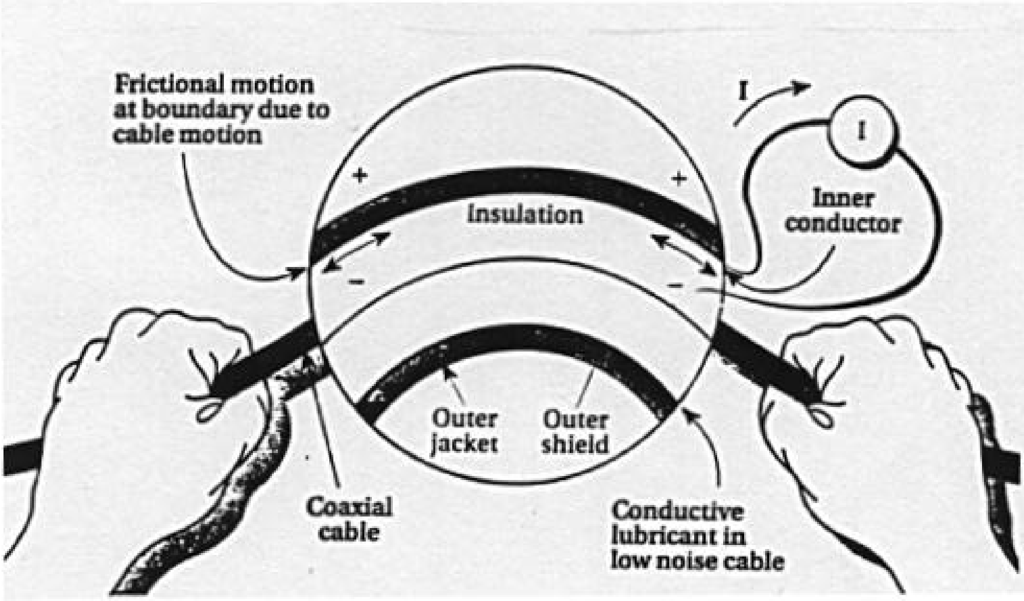

Figure 4 One foot triboelectric wire transducer, Cherokee flight