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Application of Pulse Code Modulation Technology to Aircraft Dynamics Data Acquisition

Dansen Brown*
Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio

This paper discusses the application of pulse code modulation (PCM) digital techniques to record dynamics data (20 kHz bandwidth) during flight tests. This approach is compared with current frequency modulation (FM) analog data recording technology and is found to provide a significant increase in both the dynamic range and number of data channels recorded simultaneously. The design of a PCM airborne recording system is presented which will be capable of recording simultaneously 144 channels of 20 kHz data with 66 dB dynamic range during an 8-h flight. The objective is to reduce the costs associated with flight testing required to solve vibration/acoustic problems and to define/verify design specifications.

Introduction

THE AFWAL/FIBG maintains a facility that provides dynamics data acquisition and analysis to support ground and flight testing on Air Force systems. This is primarily vibration and acoustic data of 20 kHz bandwidth. This capability is limited by the current FM analog data recording technology to the acquisition of 12 data channels simultaneously with a 40-50 dB overall dynamic range. In order to solve vibration and noise related problems and to define or verify design specifications, simultaneously acquired measurements from 100 or more different locations are frequently requested, along with a desired overall dynamic range of 60-70 dB. Frequency division multiplexing to increase the number of simultaneous data measurements beyond 12 decreases data bandwidth and degrades dynamic range. Repetition of the test condition to cycle through all transducer locations 12 at a time destroys simultaneity and significantly increases flight test costs.

FIBG had long considered meeting the desired dynamics data recording requirements by application of pulse code modulation (PCM) technology, a form of time division multiplexing featuring analog-to-digital (A/D) conversion. The multiplexing capability permits multiple measurands per tape track, and the A/D conversion prior to recording increases the dynamic range. PCM has been used to date primarily to record static or quasistatic data. Its application to high bandwidth data requires the latest high-density digital recording technology and data compression techniques. In 1979, FIBG let a contract to McDonnell-Douglas (MCAIR) to perform a study of state-of-the-art PCM technology and to design an airborne PCM dynamics data acquisition system (along with a ground based computer system to edit and analyze the large volume of digital data generated by such a system). The results of this recently completed contract was documented by MCAIR in a technical report, AFWAL-TR-81-3017, from which was derived the material for this paper.[1]

PCM Digital vs FM Analog

Flight test data can be categorized as 1) *static* data, which are relatively constant for a given period of time and can be completely described by a single measurement; 2) *quasistatic* data, which are slowly varying (such as structural temperatures) and may be characterized by relatively infrequent measurements; or 3) *dynamics* data, which oscillate rapidly generally in a random manner (vibration, acoustics, strain) and require continuous recording or high-speed sampling to recover the desired information.

Currently, aircraft dynamics data are generally acquired onboard by recording onto analog tape using FM techniques so that signal distortion by the frequency response characteristics of the recorder/reproducer are minimized. Typical airborne FM systems can record up to 14 channels of 20 kHz data for 7.5 min with an overall dynamic range of 50 dB at best (owing to the signal-to-noise ratio of analog recorders). The number of data channels could be increased by frequency division multiplexing, but this would compromise the data bandwidth and degrade the dynamic range even further. The flight test condition could be repeated with the recorder channels switched to other sets of transducers, but this destroys the simultaneity required for correlation-type analyses and increases the cost of the flight test significantly.

PCM recording has been used in flight testing primarily for low-frequency or quasistatic data due to the limited bit rate capability of systems currently in use. Since the data are encoded in digital form prior to recording, a dynamic range greater than 60 dB can easily be achieved owing to the reduction of noise and distortion in the record/reproduce process. By employing the latest PCM high-density digital recording technology, along with time division multiplexing and some form of data compression, a large number of dynamics data channels (greater than 100) can be recorded simultaneously for a long period of time (hours). This has the potential for significantly reducing flight test costs as well as increasing dynamics data quality.

Advancing from FM to PCM recording to acquire dynamics data marks one further step in the evolution from an analog to a digital process. The advent of efficient digital signal processing algorithms and inexpensive fast digital computer hardware since 1965 has made analog analysis obsolete. Application of PCM digital techniques will place the analog-to-digital conversion required for subsequent data analysis back into the data acquisition process prior to recording. This evolution is shown in Fig. 1.

Development of Goals

MCAIR performed an exhaustive literature search and vendor survey to obtain the necessary background materials and references for a detailed study of PCM system components and processes. They also performed an evaluation of the FIBG facility to obtain baseline capabilities and to identify specific requirements that would affect the design of a PCM dynamics data acquisition and analysis system. This permitted the development of goals for the PCM system which would satisfy FIBG's requirements and which had a reasonable chance to be achieved with current PCM

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*Aerospace Engineer, Contract Monitor.

technology. The major goals are presented in Table 1 along with FIBG's current capabilities (FM analog system).

Two major facility requirements were determined that mandated certain restrictions in the system design. The first, in the data acquisition process, is that many of FIBG's flight tests are conducted at various remote sites throughout the continent under test conditions that prohibit telemetry of data. Thus, onboard tape recording is the only practical means of storing large quantities of data for later processing at FIBG's home base. The second, in the data analysis process, is that cross-channel analysis may be performed on dynamics data channel pairs which are identified by various users of the data after the flight test is over. This requires all data to be acquired simultaneously and stored in the time domain, effectively ruling out some forms of onboard data compression as well as onboard analysis.

Study Areas

The primary study areas are presented in Table 2 to give an indication of the range of problems that were addressed. Two will be discussed in detail because of their relative importance in the system design.

Data Compression

The first area, multiple filter encoding, was identified early in the study as it became obvious that a scheme for onboard data compression during data acquisition was crucial in order to achieve the system goals. An 8-h recording of 144 20 kHz channels continuously sampled with 12-bit resolution (required for 66 dB dynamic range) would result in the storage of at least 2.5×10^{12} bits of information. A single 4600-ft reel of tape with 28 tracks packed at 30,000 bits/in. could store 4.6×10^{10} bits, corresponding to a maximum of 8.9-min recording time. Based on the literature search, there are six techniques for acquiring dynamics data digitally. One of these is by continuous sampling (obtaining and recording a time series of equal interval samples taking care to avoid aliasing). The other techniques take samples in a similar manner, but also involve some form of processing so that a reduction in data can be achieved prior to recording. Only the continuous sampling and multiple filter encoding methods provide enough versatility to accommodate all of AFWAL/FIBG's present and anticipated types of dynamics data analysis. Using a multiple filter encoding scheme, the storage requirements can be reduced to approximately 10^{10} bits and the 8-h goal becomes reasonable.

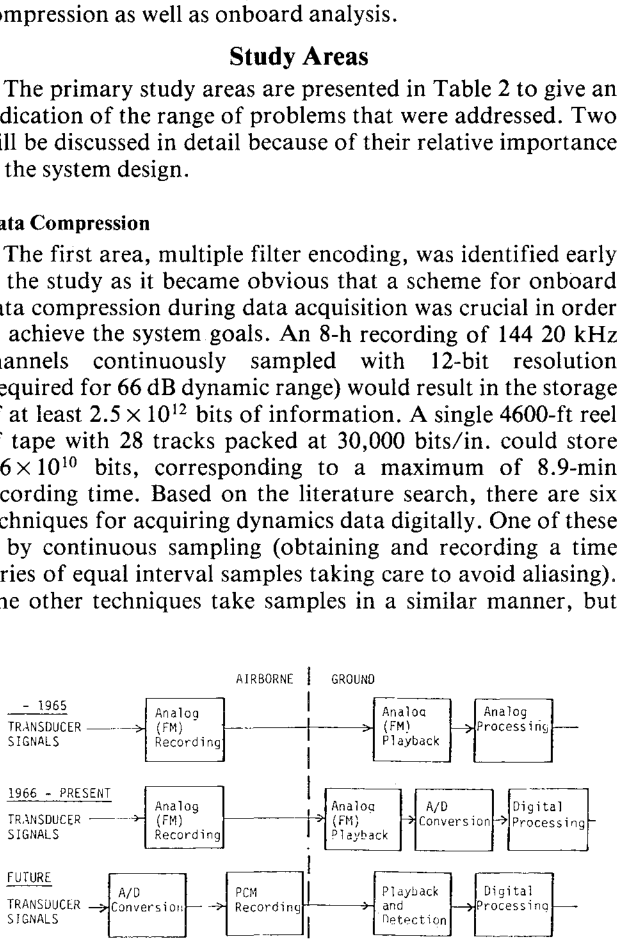

Fig. 1 Recording and processing of aircraft dynamic data.

Multiple low-pass filter encoding was found to be superior to a multiple bandpass (zoom) approach to compression. With this approach, the frequency spectrum of an incoming signal is divided up using low-pass filters with cutoff frequencies spaced some constant number of octaves apart. Each filter output is sampled by an A/D converter at a rate appropriate to the filter cutoff frequency and roll-off characteristics, for a time duration inversely proportional to the cutoff frequency. This results in an equal number of sample points taken from each filter during each "update," or cycle, through the full set of filters. By using a buffer memory to hold the output samples as they are generated, then data can be removed from the buffer at a rate equal to the time weighted average of the individual sample rates. Thus data are gathered for analysis of the entire frequency spectrum at a compressed rate. The frequency resolution of a narrowband FFT for each band of six filters with two octave band separation cutoffs is shown in Table 3 for various sample sizes.

Equations have been derived for the compression ratio, time update, and buffer storage, assuming sequential (nonoverlapped) sampling of the various filters, and equivalent characteristics for each filter. (Sequential sampling provides slightly more compression than overlapped sampling and is simpler, both from an implementation standpoint and in interpreting editing and analysis results.)

The compression ratio, or ratio of the sample rate of the highest filter to the average rate,

$$C = (D^n - 1)/n(D-1) \tag{1}$$

where n is the number of low-pass filters employed and D is the decimation ratio or ratio of sample rates of successive low-pass filters.

The time update, or the time it takes to gather N samples from all filters, one at a time,

$$T_u = N(D^n - 1)/K_l f_H (D-1) \tag{2}$$

where N is the number of samples taken from each filter during each update of the filter; f_h is the highest frequency of analysis, which is the highest filter cutoff frequency; and K_l is the ratio of sample rate to filter cutoff frequency (assumed equal for all filters).

Table 1 Acquisition goals

Acquisition standards	FIBG present capability	Goal for PCM system
Measurand channel bandwidth	DC, 20 kHz	DC, 20 kHz
Accuracy	3-5%	0.5%
Encoding resolution	12 bits + 8 levels of autorange	12 bits + 8 levels of autorange
Dynamic range	40-50 dB + 70 dB span of autorange	66 dB + 70 dB span of autorange
Number of measurands acquired simultaneously	12	144
Interchannel phase error	5 deg	5 deg
Total record time capability	7.5 min	7.5 min (transient) 8 h (stationary)
Environmental conditions	Airborne	MIL E 5400 Class 2
Airborne volume	4 ft^3	2 ft^3
Airborne weight	110 lb	50 lb
Power requirements	112 W @ 28 V DC	112 W @ 28 V DC (MIL STD 704)

The buffer storage, or buffer memory size (per measurand) required prior to the recorder,

$$M = \frac{N}{2} \sum_{k=0}^{n-1} 1 - \frac{D^k}{C} \quad (3)$$

The total number of lines or resolution resulting from merged fast Fourier transform analyses of the filter outputs, (Note: The lines are not equally spaced, except between filter cutoff frequencies.)

$$L_u \simeq \frac{N}{K_1}\left[1 + (n-1)\left(1 - \frac{1}{D}\right)\right] \quad (4)$$

The multiple low-pass encoding method is restricted for use where the overall data signal can be considered stationary for at least two or three update periods of T_u in length. For transient data, one low-pass filter is employed for continuous sampling.

Data Rate

The data compression represents only a partial solution to the problem of accommodating a large number of dynamic measurand channels in a PCM system. Clearly, higher data rates are needed than are presently available in flight test PCM hardware. The maximum bit rate for AFWAL/FIBG requirements and goals has been calculated to be 154 Mbits/s. This is based upon 144 20 kHz measurand channels with no data compression. However, the maximum bit rate that can be recorded is a function of the bandwidth available in the tape recorder/reproducer system. Considering the nonreturn to zero (NRZ) PCM codes, which are the simplest and require the least bandwidth, the highest bit rate that can be recorded is equal to twice the direct record bandwidth. Thus at least 77 MHz total recorder bandwidth is required for AFWAL/FIBG's maximum rate.

Figure 2 shows the historical progress of bandwidth capability of recorder/reproducers per IRIG standards.[2-5] It should be noted that airborne recorder capabilities have lagged the IRIG standards. The Sangamo Sabre XII recorder meets the 1977 standards (28 tracks with a 2 MHz response at 120 in./s) with an overall bandwidth of 56 MHz. Thus more than one such recorder will be required in order to handle AFWAL/FIBG's maximum data rate.

For a 144-measurand channel system, 48 tape tracks of two 28-track recorders can be employed to record three measurands each in serial PCM streams. The 48 tape tracks represent 96 MHz of total direct record bandwidth. Since 77 MHz has been established above as the minimum bandwidth necessary, this solution is potentially a satisfactory one.

However, this ignores signal-to-noise and bit-error-rate considerations in the recorder/reproducer and the PCM detection device (bit synchronizer). All tape recorder devices have poor low-frequency response (zero response at DC), yet (NRZ) PCM can have considerable low-frequency content, depending on the data activity. This results in potentially unsatisfactory performance (loss of synchronization and data dropouts). Therefore, for tape recording, the NRZ must be modified in some manner to reduce its low-frequency content. All such modifications result in an increase in required bandwidth for a given bit rate, or equivalently, an increase in required signal-to-noise ratio to maintain a given level of bit-error-rate performance. The effects of recorder/reproducer noise and distortion on the digital data will result in an occasional error in reading the encoded sample values. The theoretical bit-error probability (BEP) vs signal-to-noise ratio can be calculated as follows[6]:

$$\text{BEP} = \frac{1}{2\pi} \int_x^\infty \exp \frac{-\alpha^2}{2} \, d\alpha \quad (5)$$

where $x = 10^{dB/20}$; dB is the ½ peak-to-peak signal to rms noise ratio in dB; and BEP is the bit-error probability (multiply by bit rate to get bit error rate).

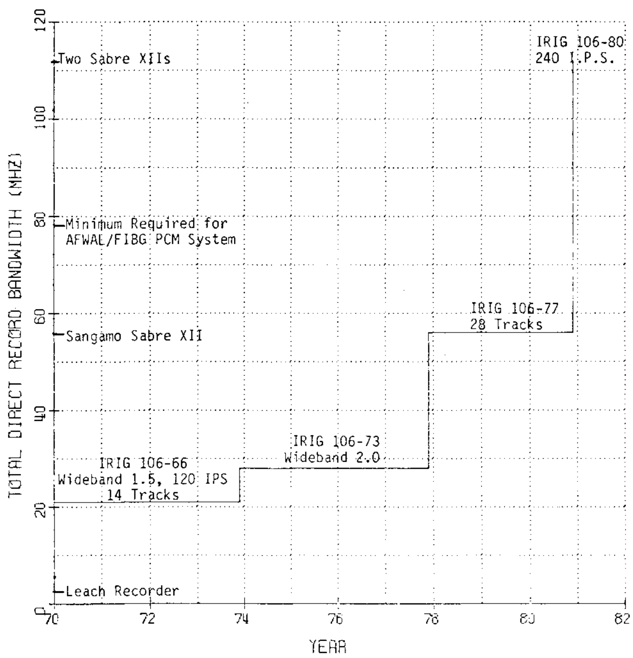

Fig. 2 Bandwidth of IRIG wideband recorders.

Table 2 Major study areas

Alternate configurations and flexibility of multiple filter encoding
Antialias filter size and complexity vs sample rate
Analog vs digital filter implementation
Establishment of recorder bit rate and storage requirements
Channel and bandwidth capacity vs recording time for stationary and nonstationary acquisition modes
Methods of encoding gain status of autorange signal conditioners
Phase matching in acquisition vs phase correction in analysis
Data validation (quick-look) at test site
Signal conditioning, including automatic gain ranging
Sampling and A/D conversion, including sample and hold
Transient response of filters
Buffer storage and formatting requirements
System calibration
Remote multiplexing concepts
Airborne subsystem size, weight, modularity, power requirements, and thermal characteristics

Table 3 FFT frequency resolution per filter band (filter cutoff frequency)

ΔF_1 (19.5)	ΔF_2 (78.1)	ΔF_3 (312.5)	ΔF_4 (1250)	ΔF_5 (5K)	ΔF_6 (20K)	Samples/filter, N
0.03125	0.125	0.5	2	8	32	2048
0.0625	0.25	1	4	16	64	1024
0.125	0.5	2	8	32	128	512
0.25	1	4	16	64	256	256
0.5	2	8	32	128	512	128
1	4	16	64	256	1024	64

The NRZ code modification adopted in IRIG 106-80 for serial high density PCM tape recording is randomized NRZ-level (RNRZ-L). This modification results in the least performance decrease of all the known serial encoding methods. It does triple the bit error rate, which is equivalent to an increase of 0.43 dB (in the vicinity of 10^{-6} BEP) in signal-to-noise ratio required to maintain a given BEP. The 0.43 dB can, in turn, be regained by reducing the recorded bit rate and, hence, the bit packing density.[7] IRIG recommends a maximum density of 25,000 bits/in. per track. The MCAIR recommended tape recorder configuration results in a tape packing density of 26,800 bits/in., thus exceeding the IRIG limit. However, manufacturers of recorders and PCM bit synchronizers claim satisfactory performance using RNRZ-L at 30,000 bits/in.[8,9] Whether or not the recommended configuration will result in a satisfactory bit-error-rate performance with the recorder in an airborne environment will be determined experimentally.

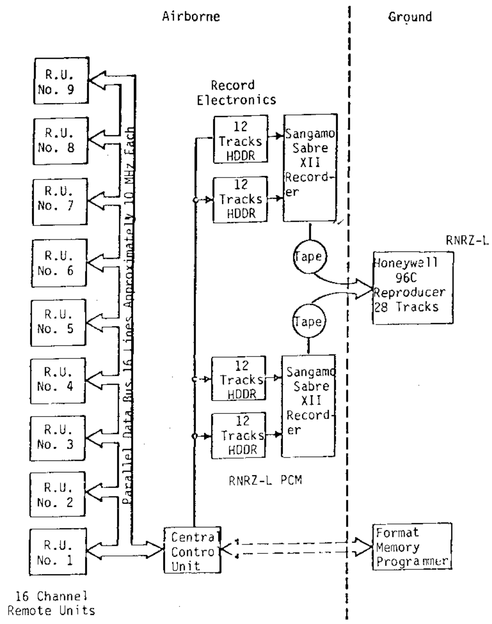

Fig. 3 Airborne PCM system.

PCM Airborne Dynamics Data Acquisition System

The system design presented herein is optimized for FIBG requirements and achieves the principal goals established in the study, including 1) 144 simultaneously acquired 20 kHz measurand channels, 2) up to 8-h record time, and 3) 66 dB dynamic range. The airborne acquisition system does not meet the goals for power (1372 vs 112 W), weight (377 vs 50 lb), and size (7.83 vs 2.0 ft^3)—this is considered by MCAIR to be a necessary consequence of using currently available technology to meet the principal goals.

An overall view of the system from transducer interface is shown in Fig. 3. The airborne system features distributed architecture with up to nine 16-channel remote encoding modules to handle 144 transducer inputs. Communication to/from the central control unit is via a 16-bit parallel bus. The rate on each of the 16 lines is approximately 10 MHz in order to handle the maximum overall data rate (approximately 154 Mbits/s) plus overhead.

Two Sangamo Sabre XII tape recorders are shown with their respective record electronics housing modules (two for each recorder). The PCM code employed is the RNRZ-L recommended in IRIG 106-80. The tape packing density resulting from the maximum bit rate is 26.8 kbits/in. The reproducer will be an existing AFWAL/FIBG Honeywell 96C modified for 28-track wideband (2 MHz at 120 in./s) direct reproduce capability. (This modification consists of new heads and additional preamplifiers.) The reproduced data are still randomized at this point since bit synchronization is required prior to derandomizing.

Power, weight, and size of the airborne modules are indicated below. Information about the PCM modules is based on design studies by SCI Systems, Inc., the subcontractor for this study. Information about the Sangamo tape recorders was taken from vendor literature data April 1979.

1) PCM remote unit: 81.9 W (including dissipation in 70% internal power supply); 24.01 lb; 0.437 ft^3 (9.75 in.

Table 4 Airborne system design features

	Mode A (transient or stationary)	Mode B (stationary)
Total number of measurands	144	144
Frequency range	DC, 20 kHz	DC, 20 kHz
Time update	N.A.	2.67-42.6 s[a]
Total record time	7.5 min	8 h
Number of filter samples	1	6
Filter cutoff frequencies	20 kHz	19.5 Hz-20 kHz (two octave steps)
Samples per cycle	3.2768	3.2768
Sample rate compression ratio	1	227.5
Samples per filter per update	N.A.	128-2048
Encoding resolution	12 bits	12 bits
Autorange	3 bits (8 steps)	3 bits (8 steps)
Number of measurands per tape track	3	6
Number of bits per word	16	16
Number of words per PCM frame	392	392
Frame rate	512/s	4.501099/s
Bit rate per track	3.21 M bits/s	28.2 kbits/s
Tape speed	120 in./s	1 ⅞ in./s
Bit packing density	26.8 kbits/in.	15.1 kbits/in.
PCM code	RNRZ-L	RNRZ-L
Number of tape tracks	48	24

[a] Proportional to samples per filter per update.

Table 5 Comparison of airborne PCM encoder/formatter characteristics

System:	TDMS	AFTIS	PDAS	Recommended
Manufacturer:	SCI	SCI	Base Ten	
User:	MCAIR	AFFTC	ADTC	AFWAL/FIBG
Total bit rate, Mbits/s	0.0388	0.512	1.2	154
Maximum number of analog measurand channels	480	960	1536	144
Maximum sample rate, s/sec	720	21,333	50,000	65,536
Data resolution, bits	8	10	11	12
Range setup				
a) Gain	Fixed	Fixed	Fixed	Automatic
b) Offset	Fixed	Fixed	Fixed	None
Maximum number of tape outputs	1	4	1	48

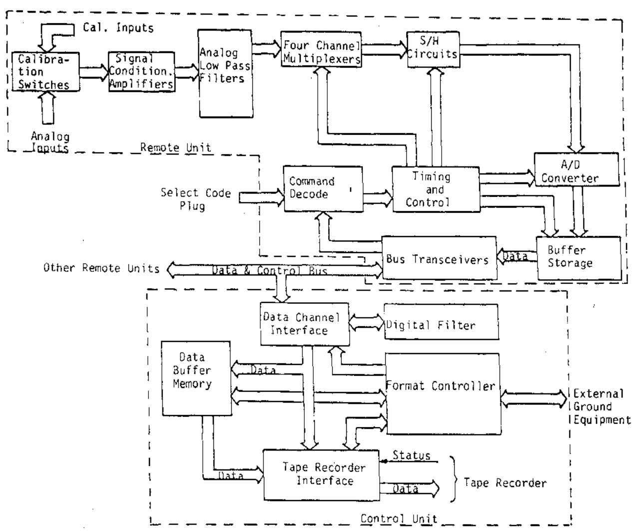

Fig. 4 PCM encoder/formatter system.

wide × 8.38 in. high × 9.25 in. long, including 0.5 in. cooling fins spaced approximately 0.45 in. apart).

2) PCM central unit: 95 W (including dissipation in 70% efficient internal power supply); 23.34 lb; 0.437 ft^3 (same dimensions and fin design as remote unit).

3) Tape transport (including tape and shock mounts): 150 W; 49 lb; 1.11 ft^3 (18.75 in.wide × 12.25 in. high × 8.375 in. long).

4) Record electronics housing: 60 W; 10 lb; 0.31 ft^3 (7.5 in. wide × 7.5 in. high × 9.5 in. long).

Figure 4 is a block diagram of the PCM encoder/formatter system, showing details of both the central and remote units. Calibration switches are shown so that an external stimulus can be applied to all data channels of a remote unit for a system through-put calibration. Signal conditioning amplifiers feature automatic gain ranging with eight gain levels. A monolithic sample and hold circuit (50-ns aperture and 0.16 W per channel) is provided to minimize interchannel phase errors. A 12-bit successive approximation A/D (32-pin hybrid module) is employed for each data channel. It consumes 1.2 W and has a 5-μs conversion time. Communication to/from the central unit is via a 16-bit parallel data bus. The data bus interface in each module dissipates 9.5 W. The central unit contains a large data buffer memory to smooth out the varying sample rates (from the different filters) to a constant rate to the tape recorder interface. The data buffer memory is over a million 16-bit words. The tape recorder interface provides NRZ-L PCM data in up to 48 separate streams. Conversion to RNRZ-L is done in the tape recorder electronics.

Figure 5 shows the recommended arrangement of six low-pass filter functions per measurand. The four highest cutoff frequency filters (312.5 Hz-20 kHz) are active analog filters located in the remote unit. One set of four such filters is dedicated to each measurand. The characteristics are type I Chevyshev, designed for 0.1 dB peak-to-peak passband ripple.[10] Cutoff frequency is defined as the highest −1.1 dB point, referenced to the DC gain. Filters of like cutoff frequency for the various measurands must be adjusted during manufacture for matching passband phase characteristics (±3 deg over the temperature range). The remaining two lowest cutoff frequency filter functions are provided by the time-shared FIR digital filter system, located in the central unit. This combination of high-frequency analog and low-frequency digital filters is shown to be optimum for this application. A 16-bit digital multiplier is required to implement the digital filters.

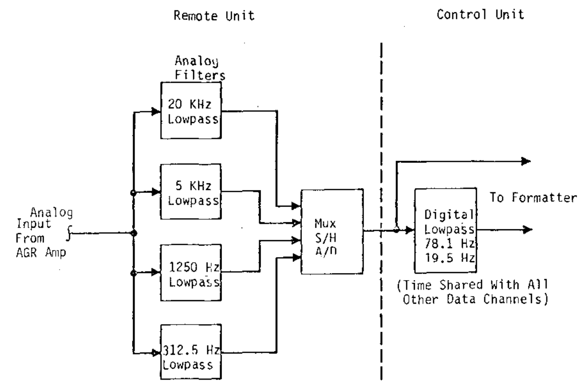

Fig. 5 Filter configuration.

Table 4 summarizes important features and characteristics of the airborne acquisition and recording system for two principal (20 kHz) operating modes. Mode A, which is suitable for either transient or stationary data, employs continuous sampling at 65,536 samples per second for each measurand, using the 20 kHz filter. Because of the high bit rate involved, the tape speed must be 120 in./s, thus limiting the record time to 7.5 min (based on a 10½-in.-diam tape reel containing 4600 ft of tape). Mode B, which is suitable for stationary data only, features multiple filter encoding for data compression so that the recorder(s) can be slowed down to 1⅞ in./s to achieve 8 h record time. Mode B, which employs all six filters, has the highest compression ratio, and allows 144 measurands to be recorded on only 24 data tracks, using a single 28-track recorder.

Table 5 shows a comparison of characteristics of this PCM system with those of three aircraft flight test PCM systems currently in use. A key feature of the FIBG system is that it will have sufficient bit rate capacity to simultaneously achieve the maximum number of measurands and the maximum sample rate per measurand. This is in contrast to the existing PCM systems which have limited bit rate capacity so that the number of measurands and sample rate for each must be traded off.

The total nonrecurring cost for development of this system (including design, breadboard, prototype, flight qualification, test equipment, system engineering, and management) was estimated to be $750K-$1000K (1980 dollars). This does not include the AGR amplifier. FIBG has initiated development of the AGR amplifier and is programming funding for the rest of the system development over the next three years.

Data Recovery and Analysis Considerations

A major consequence of recording dynamics data by PCM digital methods is the requirements levied upon the data recovery and analysis operation. One is confronted with a digital tape containing quite a large amount of data that must be decoded, demultiplexed, edited, and then analyzed. Unless these data are converted back to analog form for laborious manual editing by strip charts as is normally done for FM data, these tasks must be accomplished automatically by computer. This requires a large minicomputer (maxi) and sophisticated software to perform this type of data processing efficiently. However, given such a system, completely automatic procedures can be developed for data identification, calibration, storage into a data base system, and subsequent retrieval for analysis.

Conclusions

Flight testing requirements have evolved to the extent that a major advance in dynamics data recording is needed. Simultaneously acquired measurements from 100 or more different locations of sufficient bandwidth (20 kHz) and dynamic range (60-70 dB) are needed in order to apply the advanced digital analysis techniques to solve vibration and noise related problems and to define or verify design specifications for the increasingly complex flight systems. At the same time there are increasing pressures to reduce the length of flight tests due to the rapidly escalating costs of fuel. Current FM analog data recording technology is not capable of satisfying these requirements. However, they can be satisfied by application of the latest high density PCM digital technology and data compression techniques.

The advantages of the PCM system design presented in this paper are a dynamic range of 66 dB—made possible by digital encoding prior to recording; 144 simultaneously acquired 20 kHz measurands—accomplished by using simultaneous encoding and wide-bandwidth 28-track recorders; and up to 8-h record time for 20 kHz data—made possible by data compression.

A disadvantage is that the physical realization (power, weight, and size) of the design does not meet the desired goals as a consequence of currently available hardware technology, but with the inevitable advances in miniaturization it is felt that even these goals will be met in the near future.

Acknowledgments

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