OPTIMIZING FLIGHT SHOCK AND VIBRATION MEASUREMENT BY RF LINKS

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ABSTRACT

Acquiring shock and vibration data from flight vehicles through rf telemetry links has numerous associated challenges. Yet, these measurements are important to establish environmental specifications to provide a basis for system or component design and testing. The principal limitation in acquiring these measurements is the frequency bandwidth available for data transmission. This limited bandwidth is often responsible for invalid data being accepted as valid. This work provides a brief review of time and frequency division multiplexing to identify the potential error contributors to shock and vibration measurements. Its focus is on the design of acceleration measurement systems to eliminate these errors and optimize individual measurement channel performance.

KEY WORDS

Accelerometer, Shock and Vibration, Space Telemetry, Structural Dynamics

INTRODUCTION

A key starting point when designing a mechanical, electrical, or electro-mechanical system whose reliability must be assured is a set of specifications describing the environments the system will encounter in service. These specifications are initially based on a best estimate of the environments. This estimate usually originates from previous measurements on similar systems in similar environments. Environmental simulation testing is performed on prototype hardware during the design cycle. Ultimately, it is desired to acquire environmental measurements while the system is in its actual use conditions. These measurements enable validation or improvement of the specifications. Once validated or improved, these specifications provide a basis for environmental simulation testing of subsequent manufactured systems on either a continuous or sampling basis.

When the use conditions involve the vacuum of space, unique challenges are associated with the acquisition of the required environmental measurements. Measurement system components have to perform over a broad range of temperatures. Thermal energy can only be dissipated from these components by conduction. For satellites, long term exposure to charged particles and electromagnetic radiation can also be a problem.

Launching satellites into low earth orbits costs approximately $10,000 per pound [1]. Sub-orbital flights of sounding rockets (Figure 1) involve vehicles whose weight/payload ratio may be 20:1 to 50:1. Thus, for cost effectiveness the size and mass of the measurement system must be minimized. The electrical power requirements of the measurement system must also be minimized. An additional challenge associated with the acquisition of environmental measurements via space telemetry is limitations in available frequency bandwidth.

Mechanical shock and vibration specifications are included in any list of environmental design requirements. Accelerometers and their associated signal conditioning are used to measure component and system structural inputs and responses. For ground based testing, these measurements are transmitted via hard wire cables for recording and analysis. In the majority of situations the cable possesses more frequency capability than the accelerometer. However, in space-based testing the number and frequency bandwidth of available measurement channels is limited by the capability of the transmission system. Additional measurement channels require added accelerometers, signal conditioners, multiplexers, radio frequency transmission links, and battery power. This is in direct conflict with the stated goals of minimizing measurement system size, mass, and electrical power. Thus, acquiring shock and vibration data via space telemetry can be quite a challenge. After first reviewing the fundamentals of space telemetry, acceleration measurement systems will be described which can enhance this process.

BODY

One challenge associated with space telemetry involves combining numerous measurement channels into a single output stream that can be transmitted over a radio frequency link to a ground receiving station. Multiplexing of the channels enables this combining to occur. This multiplexing can occur either as time-division multiplexing (TDM) or frequency-division multiplexing (FDM). Two forms of TDM are pulse code modulation (PCM) and pulse amplitude modulation (PAM). PAM is the simplest form because the measurement signal on each channel can be sequentially sampled (commutated) for transmission in the form of varying amplitude pulses. To enable recovery of the sampled signal, a decommutator must be precisely synchronized to the commutator. In PCM, each PAM pulse is encoded into a binary number whose value is proportional to the amplitude. The binary number is transmitted as ones or zeros for decommutation. The radio transmitter can be frequency modulated (FM) directly in PAM by the commutated pulses (PAM/FM). For PCM the sampled and encoded signal can also directly modulate the radio frequency transmitter (PCM/FM). For both PCM and PAM, before this modulation takes place, low-pass premodulation filtering occurs. The Telemetry Group of the Range Commanders Council, representing the national test ranges of the Department of Defense, issue telemetry standards which provide the design basis for telemetry components and systems. Their most current standard is Inter-Range Instrumentation Group (IRIG) Standard 106-96 [2].

In FDM each measurement channel modulates a separate subcarrier oscillator (SCO). SCOs are alternately referred to as voltage controlled oscillators (VCOs). The SCO carrier or center frequency is frequency modulated by the input acceleration signal. The signal level might be adjusted to vary from 0-5 volts with 2.5 volts representing zero acceleration. Zero acceleration would correspond to the undeviated SCO carrier frequency so that 0 volts would correspond to the maximum negative SCO frequency deviation (negative acceleration) and 5 volts to the maximum positive SCO frequency deviation (positive acceleration). SCO outputs are mixed to form a composite signal which modulates the transmitter. The transmitted signal is received at a ground recording station where the carrier is stripped and the composite signal is processed through a group of discriminators, each tuned to demodulate a given channel. FDM is used less frequently than TDM in space based testing. However, because of the high data rates required when sampling multiple channels of shock and vibration data, FDM is the technique typically used for these applications. For fewer channels, FDM will effect significant cost savings. Figure 2 illustrates a 3-channel FDM system.

Constant bandwidth (CBW) SCO channels are used where similar bandwidth signals are present (e.g., vibration). An SCO, when modulated by a data signal, elicits a complex response containing the oscillator center frequency and an infinite number of sidebands. Sidebands with amplitude equal to 15% that of the unmodulated carrier are considered significant. The modulation index (MI) of a carrier is the ratio of f/f_s where f is the maximum deviation of the carrier above or below the center frequency and f_s is the frequency of the data. A signal with a MI of 5 would contain five significant sidebands above the data frequency.

An experimental flight of a small missile or sounding rocket might have two or three radio frequency transmitters onboard. These transmitters could transmit information regarding system or experiment state-of-health, rocket motor(s) pressure, stage separation, fireset performance, temperatures, ground command signal reception, attitude control system performance, angular rates, nose cone jettisoning, shock and vibration, and more. Figure 3 is a photograph of a typical radio frequency telemetry system being interfaced to the third stage motor of a rocket system such as is shown in Figure 1. Due to the many competing measurement requirements, it is unlikely that a single S-band transmitter would be exclusively dedicated to shock and vibration measurements. If this were to occur, the following example [3] provides some indication of the bandwidth available for shock and vibration measurements.

A given CBW 4KHz channel would require +/- 8 KHz deviation if its MI were 2. This MI would result in vibration data with about 5% accuracy. Each channel would require 16KHz data signal bandwidth. The inclusion of an associated guard band would require 32 KHz total bandwidth/channel. Eight channels would require 32 KHz times eight or 256 KHz bandwidth. Spacing below the bottom channel would require another 32 KHz frequency increment for a total system bandwidth requirement of 288 KHz. This 288 KHz would modulate the transmitter. Frequency allocation would have to be acquired from the appropriate federal authorities to transmit this signal through space. If approved, eight channels of 4 KHz shock or vibration data would result from a dedicated transmitter. Yet, many accelerometer models are capable of measuring time-varying acceleration signals with integrity to data frequencies above 10 KHz! A challenge exists in acquiring multiple channels of high frequency shock or vibration measurements via space telemetry.

The preceding discussion has provided the background to now enable the consideration of how to optimize shock and vibration measurements via space telemetry. As noted, the measurement system should have minimal mass and size and require a minimum of electrical power. In addition, the shock and vibration measurement system should only present frequencies to the multiplexer within the bandwidth capabilities of the multiplexer. The systems of today are approaching these goals. The rationale for the mass, size, and power requirements was presented previously. The rationale for restricting the frequency response of the measurement system is discussed below.

Whether TDM or FDM is used, acceleration measuring systems must be low-pass filtered before they are multiplexed. If TDM is used, filtering of the acceleration signal must occur before the commutator. This filtering prevents aliasing of data at the Nyquist frequency [1/(2 x sample rate)]. If filtering does not occur, frequencies above the Nyquist frequency are “mirrored” or “folded” around it and erroneously appear at data frequencies below it. This results in distortion of the transmitted and recorded shock or vibration signal. If FDM is used, filtering is necessary for a different reason. All accelerometers have multiple resonant frequencies with associated gain. One or more of these resonant frequencies can easily become excited by high frequency structural inputs. When this occurs, the resonant response of the accelerometer is superimposed on the signal describing the structural response of the flight system or component. These superposed signals can over deviate and distort the SCO input. Worse yet, the fact that signal distortion has occurred can remain undetected since the accelerometer resonances are obscured by the limited bandwidth of the measurement channel. Before considering how to implement the required low-pass filtering, we must first understand some details of the accelerometer/signal conditioning circuit.

The left portion of Fig. 4 represents the electrical characteristics of a piezoelectric accelerometer. This type accelerometer is typically used to measure shock and vibration in space based testing. Note that it is equivalent to a voltage generator with a series capacitor. It requires no external power. This is in contrast to an impedance type transducer that might require 20 milliamps of current independent of that required for signal amplification. Historically, piezoelectric accelerometers have also been able to be miniaturized to a greater extent than impedance type transducers.

In the early years of space telemetry, accelerometer signals were conditioned by vacuum tube circuitry. When viewing the data, uncertainty often existed as to whether the signal was attributable to the vibration response of the accelerometers or to the vacuum tube filaments! Solid state airborne charge amplifiers evolved in the middle 1960s and replaced the vacuum tube circuitry. Depending on their design options, each amplifier was 3-4 cubic inches in volume and weighed 3-5 ounces. By the early 1970s, subassembly modules fabricated with thick and thin film technology enabled further miniaturization of these amplifiers. They subsequently occupied about 1 cubic inch and weighed approximately 1 ounce. Contingent on the cable length between the accelerometer and the amplifier, an accelerometer/cable/amplifier system might weigh 1½ - 2 ounces. Figure 5 illustrates one such system. This particular system provided a low impedance 0-5 volt output signal which could be center-biased to 2.5 volts. The amplifier operated from a 20-32 VDC unregulated supply while drawing about 25 milliamps of current. Its thermal operating range was from -67 to +212^{o}F and its shock survival capability was 100g. Low noise accelerometer signal cable was required. Cable tie down further precluded motion induced cable noise from entering the amplifier. These systems were used on the Atlas, Ariane, and Delta II rocket systems. Figure 4 illustrates the electrical characteristics of one such system and its contained filtering. Note that this filtering occurs between the charge converter and the second stage gain of the charge amplifier.

The technology of today enables signal conditioning to be integrated into the accelerometer housing. This minimizes size, weight, and power requirements. It also eliminates any charge generated noise due to motion of the accelerometer cable. Reliability is increased since cable/connector interfaces between the accelerometer and amplifier are eliminated. More important, much more effective filtering of the signal from the accelerometer is occurring. This effective filtering is the key to success when transmitting shock and vibration data via telemetry.

It was explained why multiplexed acceleration measuring systems should contain low-pass filtering. The optimum location for placement of the filter is considered next. This location is immediately at the output of the piezoelectric accelerometer. This location is optimal for several reasons.

1. Meaningful channel calibration limits are established.

   Due to experience with previous flight systems, or finite element analysis, the structural dynamicist can establish meaningful measurement channel calibration limits for the mechanical response of the flight system. However, neither experience nor analysis enables reliable limits to be established when the structural resonant characteristics of an accelerometer become excited. This excitation occurs at frequencies above the predictive response of the flight system (10s of KHz). If high frequency inputs (e.g. pyrotechnic shock) excite these resonances, they superpose on the low frequency mechanical response signals. This superposition can overdrive measurement system components causing signal amplitude and frequency distortion.

2. Signal distortion can be identified.

   Filtering at the accelerometer output can immediately constrain signal frequency content to the bandwidth of the multiplexed system. The remaining signal represents the flight system or component's structural response. If this signal exceeds the amplitude limits of the channel, evidence of it will be contained in the recorded signal. If filtering were to occur in subsequent signal conditioning components, it could obscure the fact that channel amplitude limits were exceeded.

3. The signal/noise ratio of each multiplexed channel is optimized.

   If the signal bandwidth is constrained at the output of the accelerometer, a lower amplitude signal results. High gain can be applied in the first stage amplifier as opposed to a later amplifier stage. In any measurement system with cascaded gain, a high first stage gain will optimize the measurement system signal/noise ratio. Gain at subsequent locations will amplify both signal and noise from the previous stages.

Returning to Figure 4, we can now see a pitfall with this system; the filter location is not optimized. However, the option of simply inserting a commercial analog filter at the output of the piezoelectric accelerometer doesn't exist. Piezoelectric accelerometers have output impedances on the order of 10^{10} ohms. How to implement this low-pass filtering must next be considered. This implementation must also consider the size, weight, and power constraints recognized earlier.

Figure 6 is a photograph of a small (< 1 ounce) piezoelectric accelerometer with integral electronics. Figure 7 describes its contained electrical circuit. This acceleration measuring system is optimized with several essential features. It operates from 15 to 32 VDC, is biased at 2.5 volts, has an electrically isolated signal ground, has a 360^o mounting orientation, is hermetically sealed, has a volume of approximately 0.3 cubic inches, and nominally draws 15 milliamps of current. Thus the goals of size, weight, and power minimization are much better achieved than with the previously described shock and vibration measurement systems. It also operates over the same -67 to +212^{o}F temperature range as these systems. Cable induced noise between the piezoelectric element and the amplifier is no longer a concern. More important, filtering occurs immediately at the output of the accelerometer where it has been identified to be the most effective. This filtering is accomplished by a junction field effect transistor (JFET) first stage that enables two filter poles. The high JFET input impedance, when coupled with the capacitance of the piezoelectric element, also ensures an adequate circuit low frequency time constant. A second two pole filter, built around an ensuing active circuit element, provides an overall four pole low-pass filter response. Passive feedback components within the circuitry control both gain and filter bandwidth. Figure 8 illustrates various filter roll off options. Thus this acceleration measuring system offers significant performance enhancements. An early product application of this accelerometer system is the Sea Launch Program, an international venture lead by Boeing to launch large payloads from a semi-submersible platform at sea.

CONCLUSION

Many challenges are associated with acquiring meaningful shock and vibration data via space telemetry. The limitation in available frequency response creates the principal challenge. Size, weight, power, and thermal requirements provide additional constraints. Acquiring successful measurements depends on an understanding of (1) the dynamic response of the flight vehicle system, (2) the airborne telemetry system, and (3) the acceleration measuring system. In addition, compatible interfaces between these systems must be established. Advances in measurement technology (Figures 6, 7, and 8) are enabling better structural dynamics data to be acquired through rf telemetry links.

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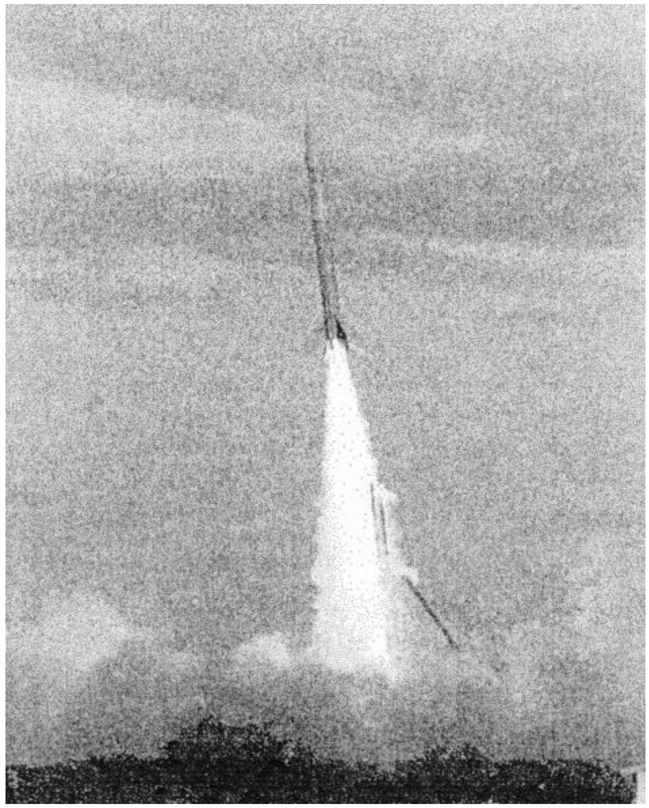

Figure 1: Sub-orbital Sounding Rocket Experiment

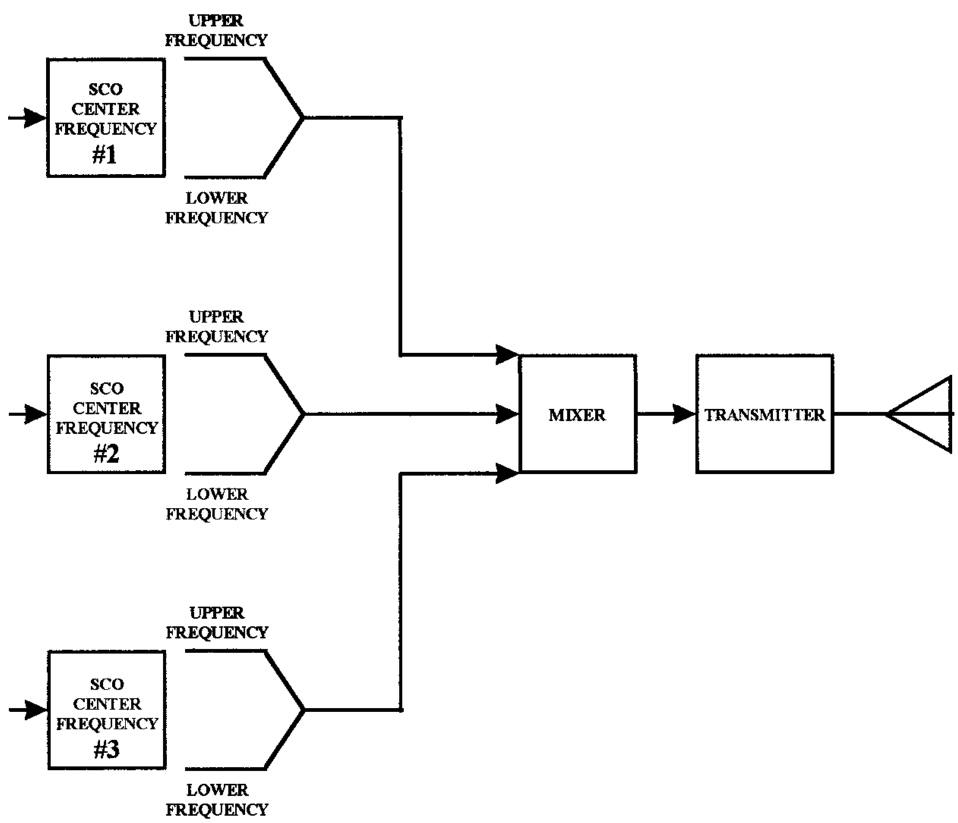

Figure 2: Three-Channel FM System

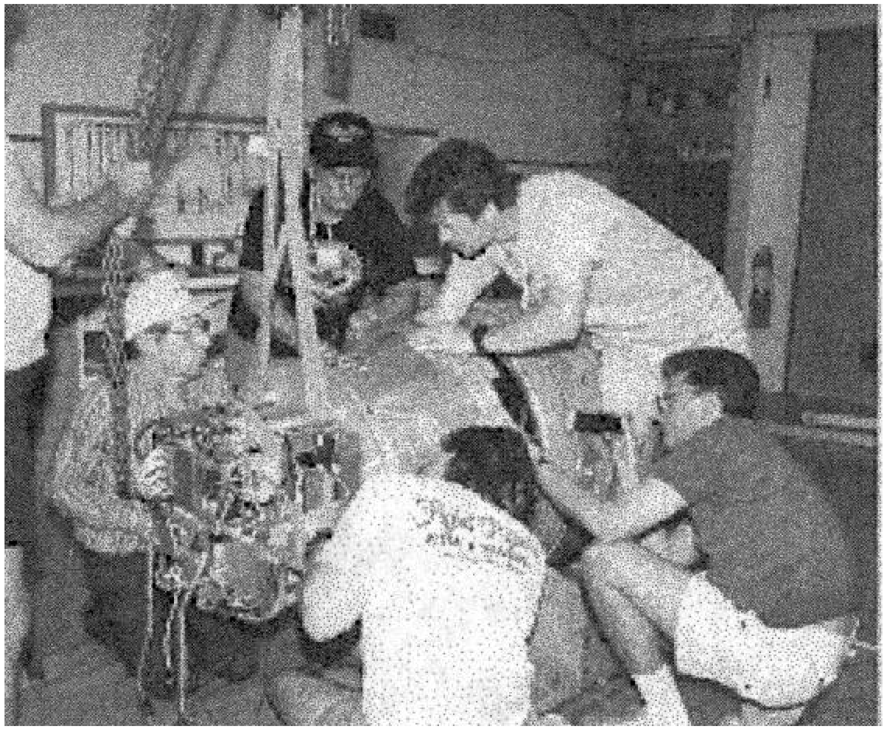

Figure 3: "State of Health" Telemetry for Sounding Rocket (Sandia National Labs)

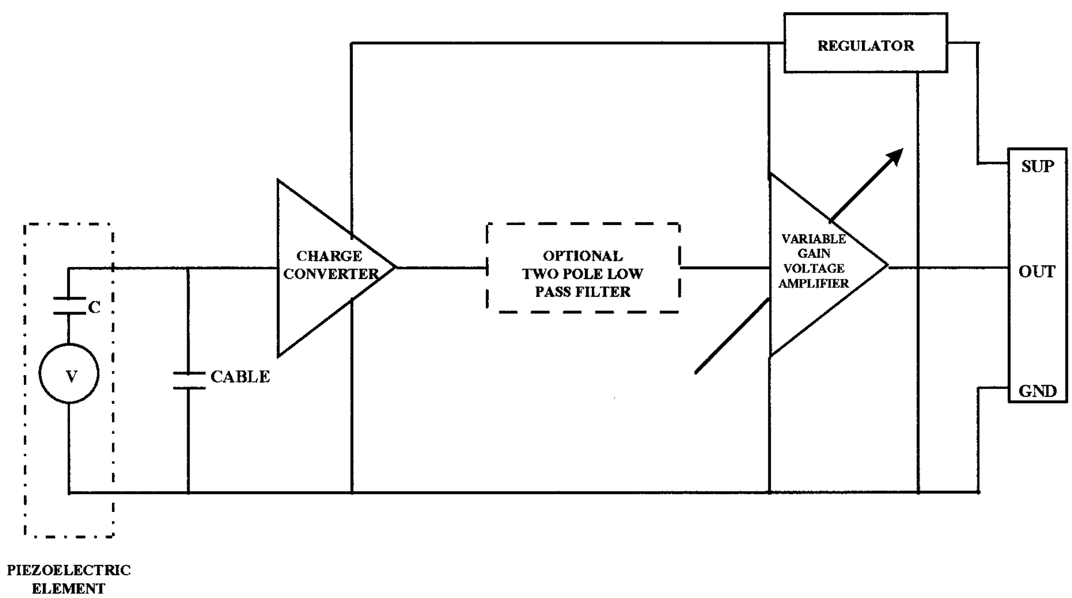

Figure 4: Charge Amplifier With Optional Filter

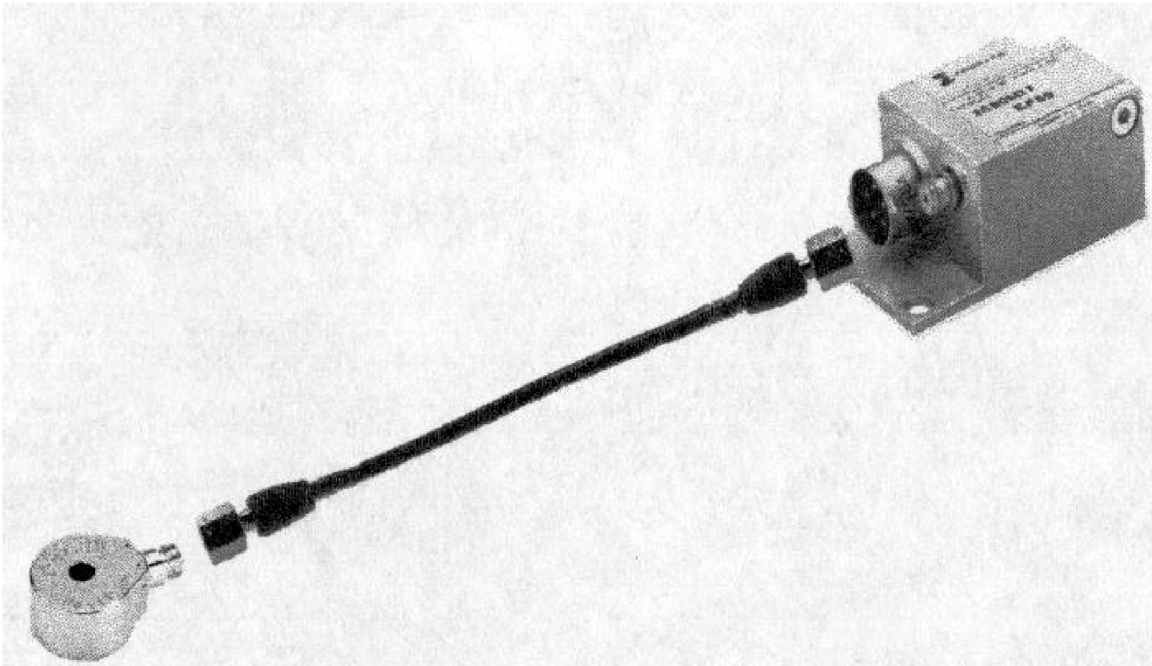

Figure 5: Accelerometer/Cable/Charge Amplifier System 1970s Technology (courtesy Endevco_

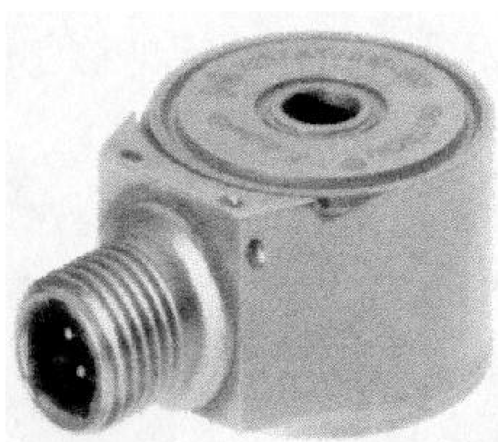

Figure 6: Endevco Model 7257 Telemetry Accelerometer

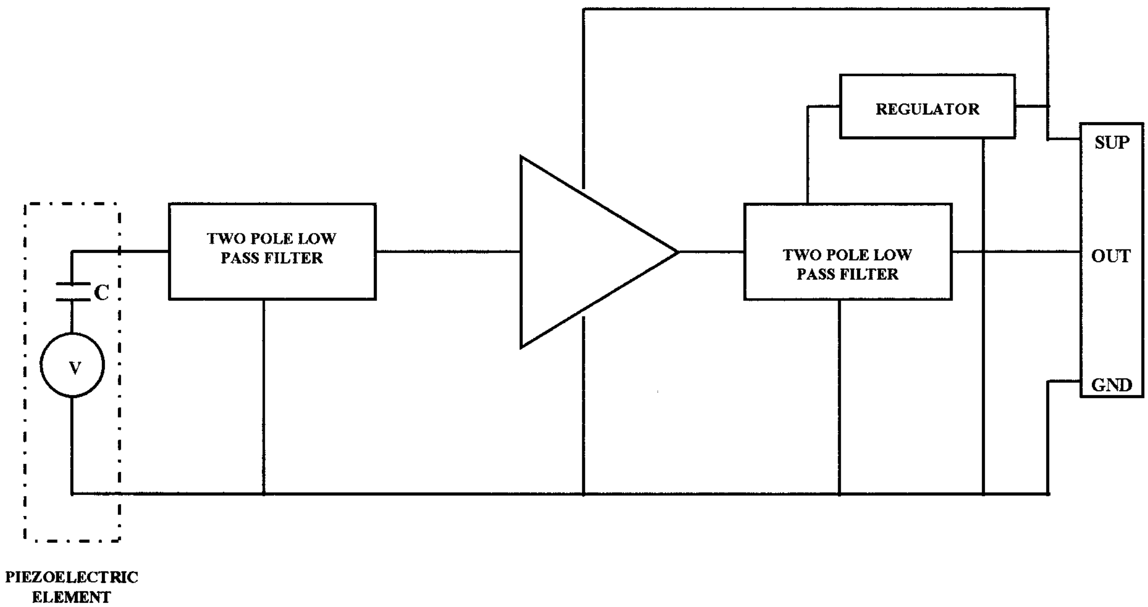

Figure 7: Endevco 7257 Circuit

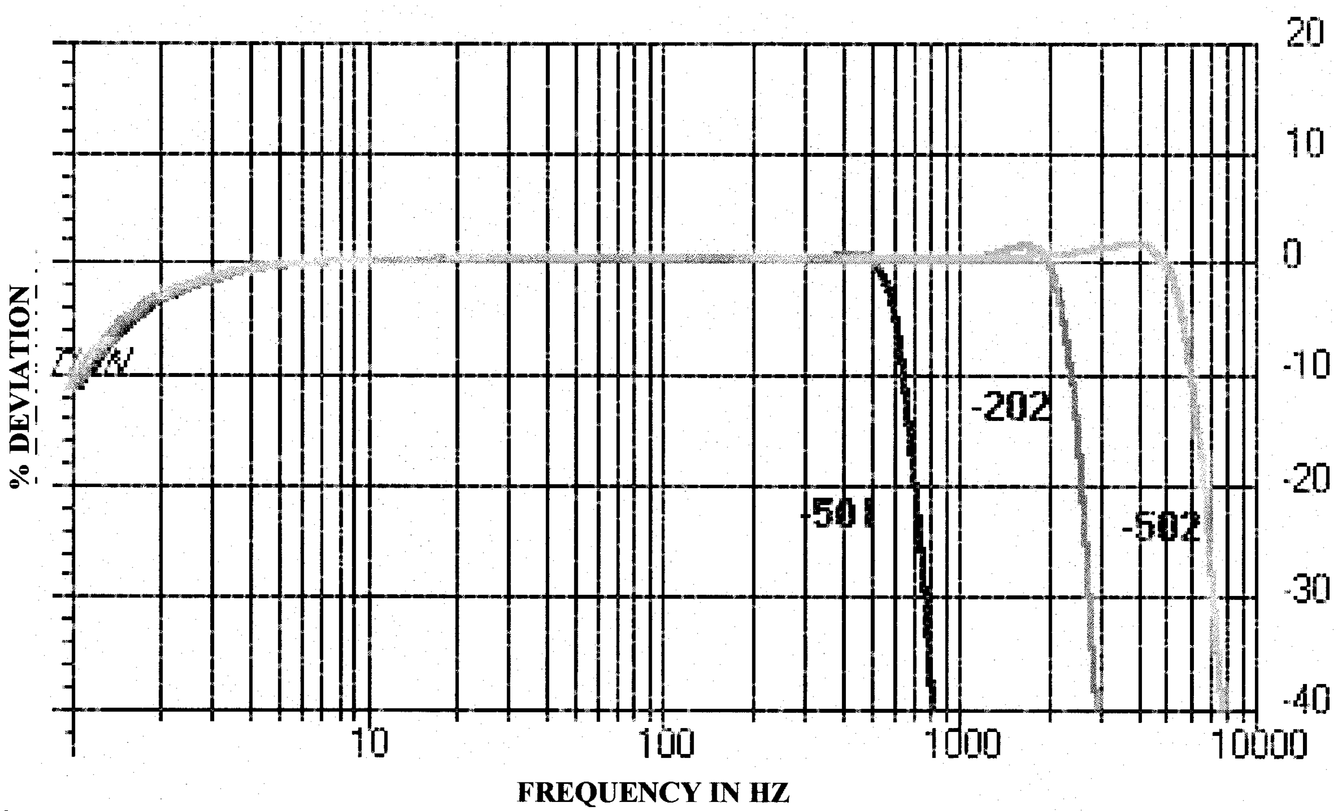

Figure 8: Typical Endevco 7257 Low Pass Filter Options for Multiplexing Compatibility