Multiplexing Technology for Acoustic Emission Monitoring of Aerospace Vehicles
Proceedings of the 4th International Workshop on Structural Health Monitoring 2003

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ABSTRACT

The initiation and propagation of damage mechanisms such as cracks and delaminations generate acoustic waves, which propagate through a structure. These waves can be detected and analyzed to provide the location and severity of damage as part of a structural health monitoring (SHM) system. This methodology of damage detection is commonly known as acoustic emission (AE) monitoring, and is widely used on a variety of applications on civil structures. AE has been widely considered for SHM of aerospace vehicles. Numerous successful ground and flight test demonstrations have been performed, which show the viability of the technology for damage monitoring in aerospace structures. However, one significant current limitation for application of AE techniques on aerospace vehicles is the large size, mass, and power requirements for the necessary monitoring instrumentation. To address this issue, a prototype multiplexing approach has been developed and demonstrated in this study, which reduces the amount of AE monitoring instrumentation required. Typical time division multiplexing techniques that are commonly used to monitor strain, pressure and temperature sensors are not applicable to AE monitoring because of the asynchronous and widely varying rates of AE signal occurrence. Thus, an event based multiplexing technique was developed. In the initial prototype circuit, inputs from eight sensors in a linear array were multiplexed into two data acquisition channels. The multiplexer rapidly switches, in less than one microsecond, allowing the signals from two sensors to be acquired by a digitizer. The two acquired signals are from the sensors on either side of the trigger sensor. This enables the capture of the first arrival of the waves, which cannot be accomplished with the signal from the trigger sensor. The propagation delay to the slightly more distant neighboring sensors makes this possible. The arrival time from this first arrival provides a more accurate source location determination. The multiplexer also identifies which channels are acquired by encoding TTL logic pulses onto the latter portion of the signals. This prototype system was demonstrated using pencil lead break (Hsu-Neilsen) sources on an aluminum plate. It performed as designed providing rapid low noise trigger based switching with encoded channel identification

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This multiplexing approach is not limited to linear arrays, but can be easily extended to monitor sensors in planar or three dimensional arrays. A 32 channel multiplexing system is under development that will allow arbitrary sensor placement. Another benefit of this multiplexing system is the reduction in the expense of data acquisition hardware. In addition, the reduced weight and power requirements are of extreme importance for proposed AE systems on aerospace vehicles.

INTRODUCTION

In acoustic emission (AE) monitoring, there is often a trade-off between the number of AE sensors needed to provide sufficient coverage for accurate source location and detection of all significant signals, and the expense of the required instrumentation. In addition to cost, the size, weight, and power requirements of AE hardware are further limiting factors for air and spacecraft applications. The ability to multiplex a number of AE sensors into the same data acquisition hardware could significantly reduce the cost, size, weight, and power requirements of an AE monitoring system. This capability would make health monitoring of large structures with AE both more practical and reliable.

Typical AE instrumentation consists of the following components: sensor, preamplifier, signal conditioning module, data acquisition hardware, and computer for analysis. Typical sensors and preamplifiers used are relatively inexpensive. They are also small, lightweight and consume little power. The signal conditioning module (SCM) provides additional amplification, filtering, and signal triggering for the acquisition hardware. The SCM for a general purpose AE system, which offers a variety of settings (gain, filtering, and trigger threshold) is more expensive than the sensors and preamplifiers. However, the cost, size, and power requirements for a SCM can be minimized by designing it for a specific testing application that would require only limited setting selections. The most expensive hardware component in an AE monitoring system is usually the data acquisition system. AE data acquisition systems are also relatively bulky and consume significant power.

Thus, a significant impact on reducing cost, size, weight, and power needs for an AE system is to be gained from eliminating data acquisition hardware. Multiplexing, or high speed switching of a large number of sensor signals into a smaller number of data acquisition channels is a natural approach for this problem. However, most currently available multiplexing systems are based on time division multiplexing (TDM). TDM works well when the measurement parameter (i.e., strain, pressure, temperature, etc.) is varying relatively slowly in time with respect to the speed at which the multiplexing switching occurs. TDM has been applied for limited cases in vibration and AE measurements in which the signals are at relatively constant levels and vary slowly in time [1-3]. However, for most AE applications, the signals are asynchronous and may change quickly in time and thus TDM is not a satisfactory approach.

In this work, an event based AE multiplexing approach has been developed and a prototype multiplexing circuit built and successfully tested. Smart, fast switching is used to allow the signals from the nearest neighboring sensors of a triggered sensor to be passed through to the acquisition hardware. For a linear source location application (e.g. pipe or beam monitoring), the signals from two sensors on either side of the triggered sensor are captured and analyzed. For planar or three dimensional source location, signals from increased numbers of adjacent sensors around the triggered sensor will be acquired.

One important consideration for AE data acquisition is the so-called dead time during which the system cannot acquire a new AE signal because the system is acquiring and storing data from a previous event. In a multiplexing AE system, this dead time affects all sensor channels, not just the sensors being recorded. This will ultimately limit AE event acquisition rates, and at high event rates, it is possible that some signals will be missed. However, for many applications such as impact monitoring on spacecraft and fatigue crack growth in metals, the event rate may be sufficiently slow as to not present a problem. Furthermore, the dead time is affected by the triggering method. In many waveform based (digitizing) AE systems the trigger method is one channel trigger, all channels trigger. With this method, signals of most interest are often only detected by a few sensors close to the location of the event, with the other channels monitored recording no signals. The data acquisition rate for a multiplexing system would be the same as for such a one-channel, all-channel trigger system. However, fewer data acquisition channels would be required. Thus, data storage and analysis requirements, which are also often significant limitations, would be significantly reduced.

PROTOTYPE LINEAR LOCATION MULTIPLEXING SYSTEM

A prototype linear location multiplexing AE system has been developed and successfully tested. The multiplexing system consists of 8 sensor channels that were multiplexed into two data acquisition channels. A block diagram of this multiplexing system is shown in Figure 1. For this system, each sensor channel has its own preamplifier (PA) and SCM channel. The SCM channels provide conditioned signal output as well as an independent trigger signal to the multiplexing system. The SCM for the sensor nearest the AE source generates the trigger signal to initiate operation of the multiplexing circuit. Using this trigger, the multiplexing circuit then switches to allow the conditioned signals from the two neighboring sensors to be passed to the two data acquisition channels. It also passes the trigger signal along to trigger the two data acquisition channels. The signals from the two neighboring sensors are used instead of the actual triggered sensor to allow capture of the full waveforms. Often, the earliest portion of an AE signal is of small amplitude and below the trigger level. If the signal from the triggered sensor were acquired, this early arrival information, which is most crucial for accurate source location determination, would be lost. Because of the time delay for signal propagation to the neighboring sensors, full waveforms are captured on these sensors, which enables accurate source location. However, if the trigger sensor is generated by either one of the outermost sensors on the ends of the linear sensor array, then the signals to be acquired are designated to be the trigger sensor and the one adjacent to it. In this case, the signal either originated between the last two sensors or outside the sensor array. With the sensors numbered as 0 through 7, with 0 and 7 being the two ends of the array, the multiplexing switching occurs as indicated in the Table I.

In addition to sending the conditioned signals and a trigger signal, the multiplexing circuit also provides information about which sensor signals are being recorded. To accomplish this, the latter portions of the conditioned signals from the two sensors being acquired are blanked out. Binary encoding pulses at a specific time (relative to the trigger signal) during this blanked out portion of the signals are used to encode which sensor signals are being acquired. The analysis software then detects and decodes these coding pulses to properly locate the AE source relative to the correct sensors in the linear sensor array.

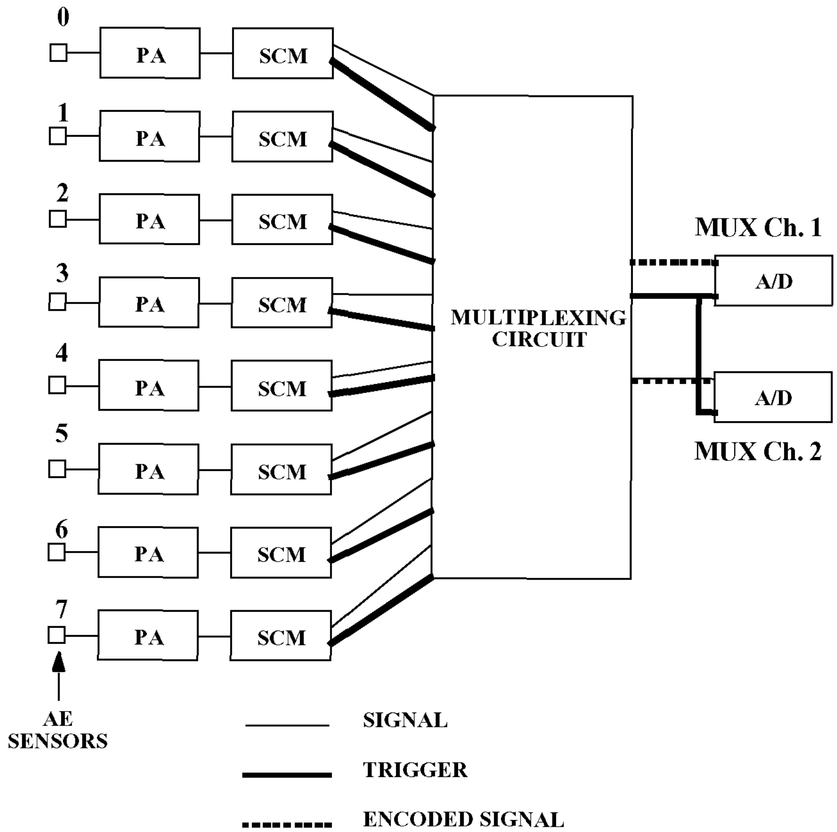

Figure 1. Block diagram of prototype linear array AE multiplexing system

TABLE I: Channel switching configuration for prototype multiplexing system

Trigger Sensor	Sensor Signals Sent to Acquisition Hardware
0	0 and 1
1	0 and 2
2	1 and 3
3	2 and 4
4	3 and 5
5	4 and 6
6	5 and 7
7	6 and 7

PROTOTYPE SYSTEM TESTING

To test the prototype linear array multiplexing system, eight broadband AE sensors (Digital Wave Corporation model B1025) were positioned in a linear array on a 3.175 mm thick aluminum plate specimen as shown in Figure 2. Simulated AE signals (pencil lead breaks) were performed at different locations as shown in Figure 2 to test the system. A 30 MHz sampling frequency was used to acquire 4096 point waveforms with a Digital Wave Corporation (DWC) Fracture Wave Detector AE system. A typical set of plate mode waveforms acquired from these experiments is shown in Figure 3. For the signals in this figure, the source was positioned adjacent to sensor 1. Thus, the signal from sensor 0 is recorded on MUX Channel 1 and that from sensor 2 on MUX Channel 2. The channel identification is indicated by the digital encoding on the end of the signals. Since the source is midway between sensors 0 and 2, the waveforms are nominally identical and arrive at nominally the same time. The linear location software of this system was modified to read in the channel encoding and then perform the linear location relative to the acquired two channels. The linear location is then plotted along with the positions of all sensors, showing the actual location along this array. Although equal sensor spacing was utilized for these demonstration tests, this is not a requirement.

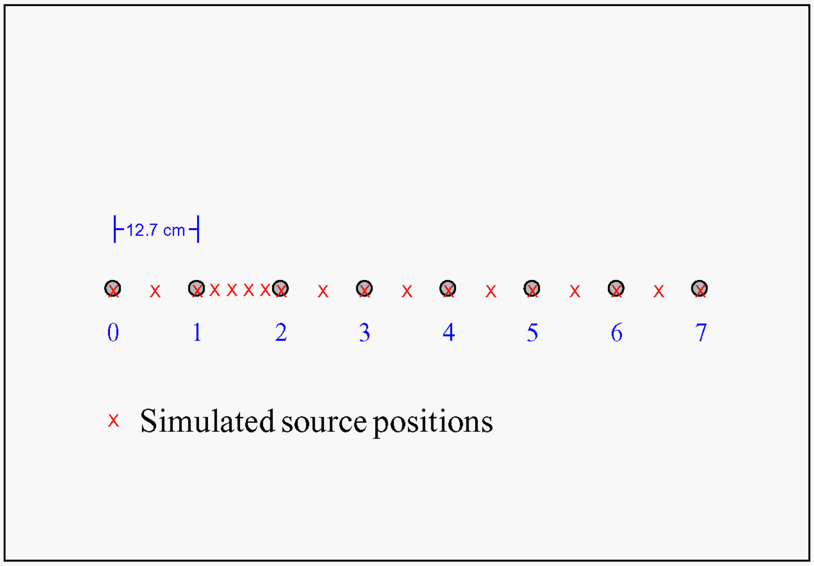

Figure 2. Positions of sensors and source positions for AE multiplexor system testing.

For this multiplexer configuration, there are two source location cases that create difficulty for analysis. The first is if the source is located exactly half way between a pair of adjacent sensors. In that case the signal arrives nearly simultaneously at the two sensors generating a trigger at nominally the same time. The multiplexer deciphers which sensor generated the first trigger or if a tie, defaults to the lowest number sensor and passes the appropriate two sensors signals to the data acquisition hardware. The difficulty occurs because the signal arrives at one of the adjacent sensors at nominally the same time as that of the trigger sensor, there is no propagation delay to enable capture of the earliest signal arrival. An example of this case is shown in Figure 4 in which the source was located at the midpoint between sensors 5 and 6. The signal from sensor 5 is acquired on MUX Channel 1 and that from sensor 7 on MUX Channel 2. The rapid switching speed of the multiplexer minimizes problems associated with this source position, but some degradation in source location occurs when using first threshold crossing location methods. Performing source locations on the more slowly propagating and highly dispersive flexural mode using algorithms, such as the cross correlation method developed by Ziola et al. [4], would eliminate this problem.

The second problematic source location is that near one of the end sensors or outside the sensor array. Sources outside the sensor array are always a problem in

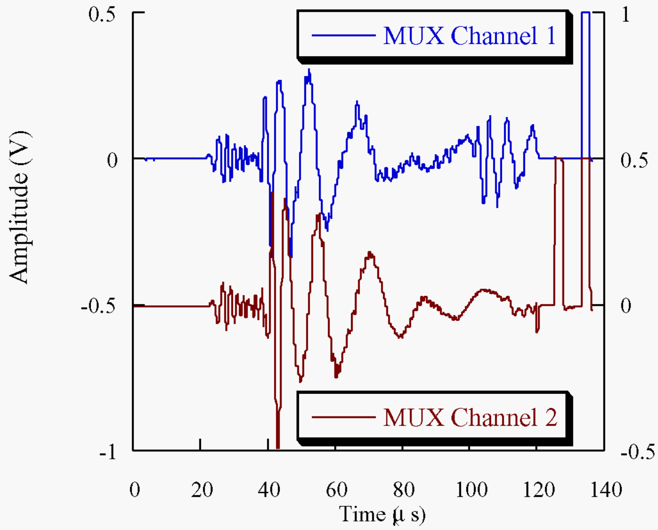

Figure 3. Multiplexed AE signals for source adjacent to sensor 1.

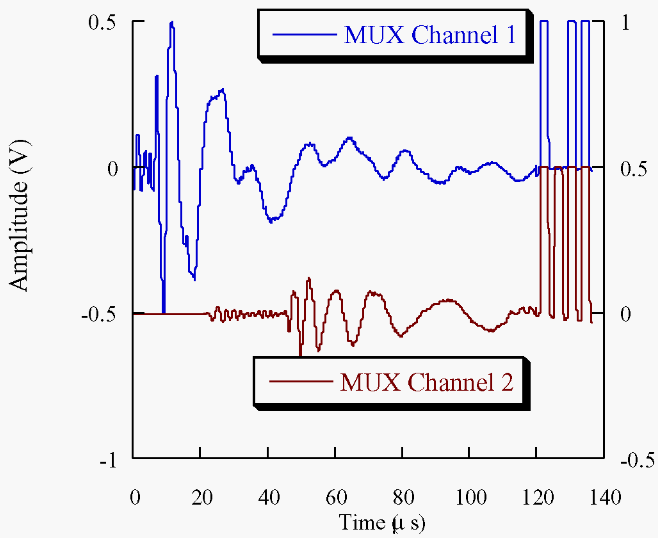

Figure 4. Multiplexed AE signals for source midway between sensors 5 and 6.

linear location schemes as they provide a constant time of arrival difference between sensor pairs regardless of the distance to the source location. Thus, such sources are not locatable. However, with the multiplexer, sources inside the sensor array but closest to the endmost sensor are also difficult to precisely locate. For these cases, the signal is captured from the sensor that generated the trigger and thus the pretrigger early arriving signal is lost. An example pair of signals for such a case is shown in Figure 5 where the source was located near sensor 7. The signal from sensor 6 is shown on MUX Channel 1 and that from sensor 7 on MUX Channel 2. It still might be possible to locate sources based on such truncated signals by comparing them to modeled or experimentally measured signals over a range of source locations in the region. However, further study is needed to develop such an algorithm.

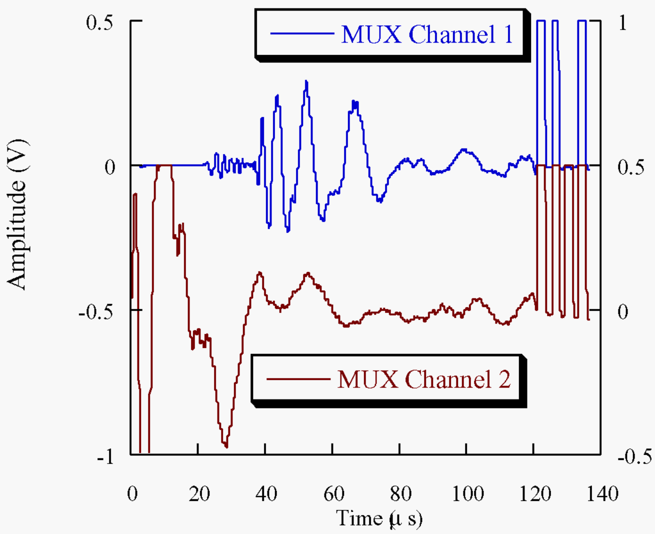

Figure 5. Multiplexed AE signals for source near sensor 7.

ARBITRARY SENSOR ARRAY MULTIPLEXER DEVELOPMENT

Based on the successful testing of the 8 channel linear array multiplexer, design has been initiated on a 32 channel multiplexer circuit. The 32 channel version has a number of differences and improvements. First it is not limited to linear array configurations (i.e., switching to acquire only two channels). It can switch to acquire up to a maximum of 8 channels, thus enabling the monitoring of sensor arrays to perform linear, planar, or three dimensional source location with redundancy. In addition, this system is not hardwired to acquire specified sensor numbers based on the channel triggered. The number of sensors to be acquired, and the configuration of which sensors are to be acquired for a given sensor channel trigger is designed to be software programmable. Thus, the multiplexing configuration can be customized for a given testing application. In addition, the multiplexing system is designed so that multiple 32 channel multiplexer circuits can be ganged together providing for monitoring of even larger numbers of sensor channels.

The multiplexer circuit itself is contained within a single integrated circuit (IC). This circuit monitors the trigger outputs of the signal conditioning electronics and generates appropriate control signals to route the desired AE data to the data acquisition system (DAQ) for processing and event location discrimination. A similar binary coding scheme is used to provide channel identification to the data acquisition software. As shown in the block diagram of Figure 6, the multiplexer IC contains four functional blocks: a trigger detection circuit, a steering logic circuit, and delay generator circuit, and an encoder circuit. The trigger detection circuit monitors the 32 trigger inputs and passes on the channel number of the trigger source to the steering logic when a valid trigger has been obtained. Additionally, the trigger circuit starts the delay generator and locks out any additional trigger events until the end of the data acquisition cycle. The circuit also generates a trigger out signal to disable any other multiplexer IC of lower priority and monitors a cascade trigger input from any higher priority multiplexer IC. The steering logic circuit takes the valid trigger channel number from the trigger detection circuit and compares it to the configuration data. It then generates the necessary control signals for the external analog switches and notifies the encoder circuit which AE signal channels are being routed. When the delay generator determines that the data acquisition cycle is complete, it resets the steering logic and notifies the encoder to begin generating the binary code for each AE channel routed to the DAQ. Once the channel numbers have been written to the appropriate DAQ channel, the encoder resets the multiplexer IC and enables the trigger detection circuit to begin monitoring for active trigger events once again. Preliminary design of this 32 channel multiplexing system has been completed. The fabrication and testing phase of this project is underway.

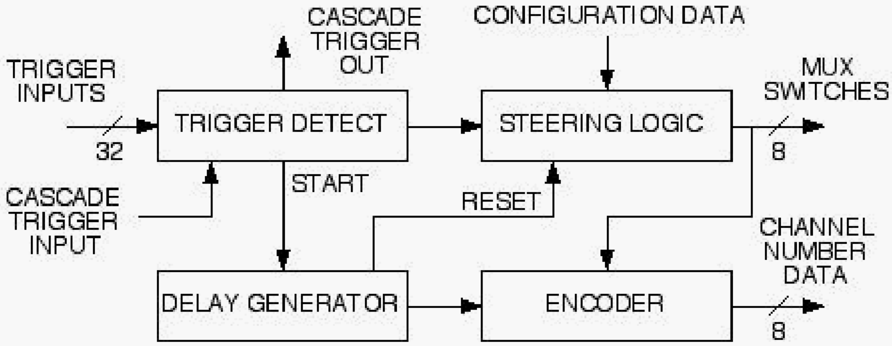

Figure 6. Block diagram for 32 channel multiplexer design.

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