Data Validation: A Requirement for Enabling Data Uncertainty Analysis

Prepared for the Transducer Workshop of the Telemetry Group of the Range Commander's Council

May 20/21, 2006 Fort Worth, TX

Patrick L. Walter, Ph. D., P.E.

Engineering Faculty Texas Christian University

Let's catch your attention!

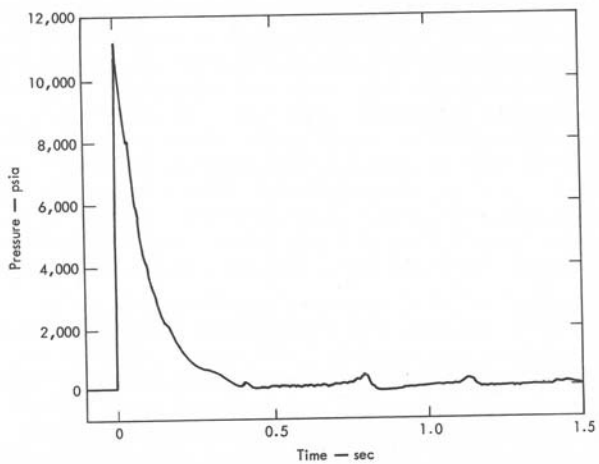


Fig. 7. Output of 0-10,000 psia blast-pressure transducer, showing full-scale transient due to radiation sensitivity.

Pressure transducer exposed to dynamic pressure peak of 750 psia concurrent with radiation environment

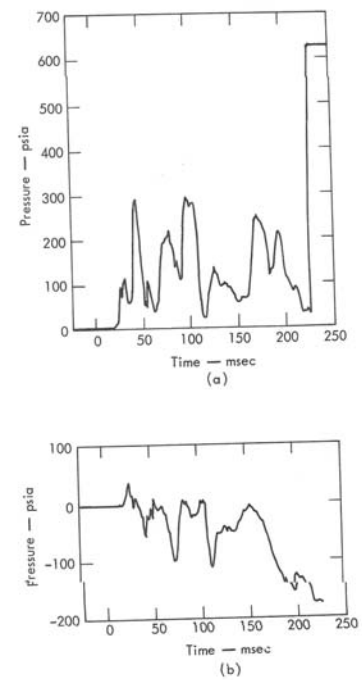
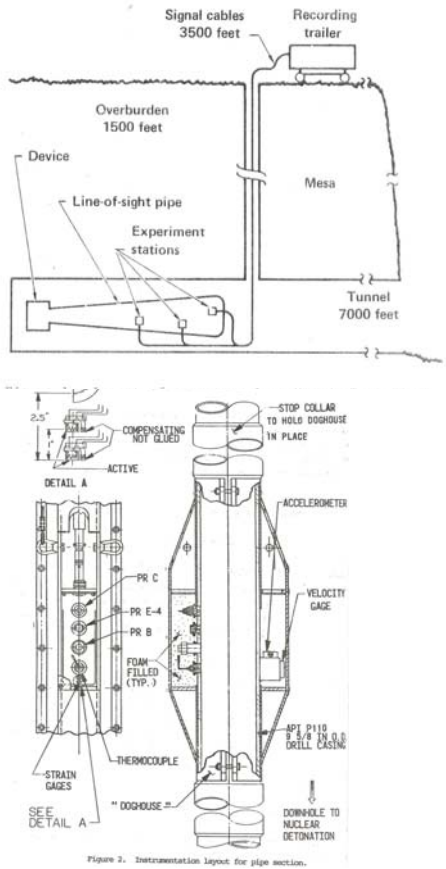


Fig. 3. Records from two gas-pressure transducers at the same location, showing shock sensitivity. No real-gas pressure was observed.

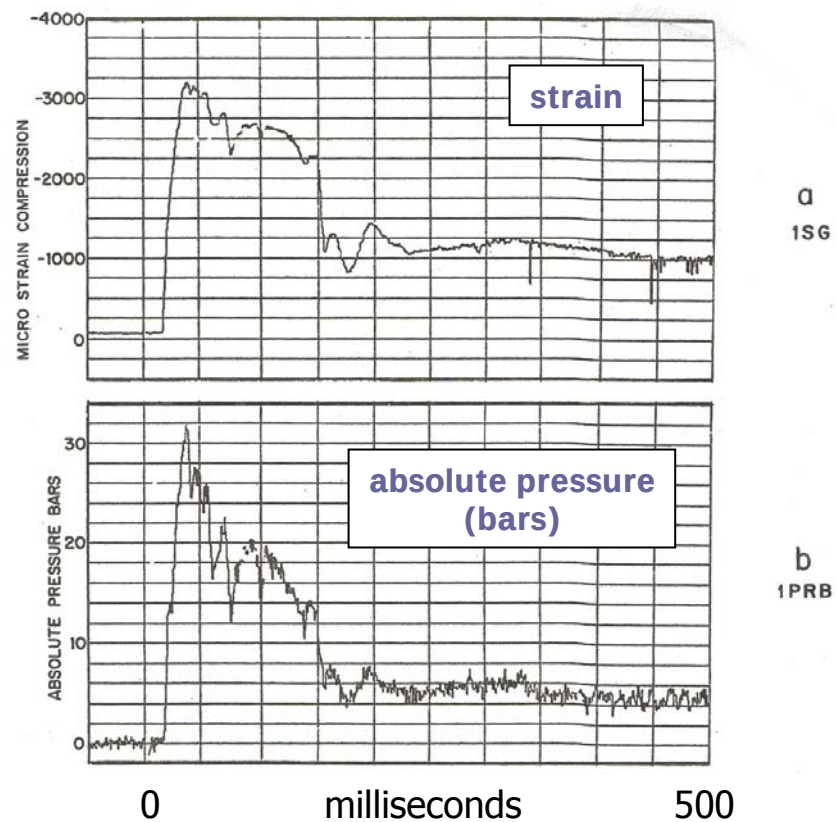
Two pressure transducers encountering mechanical shock with the pressure environment absent

Olsen, Diagnostic Problems Related to Measurements Near Underground Nuclear Detonations, 7th Transducer Workshop

Let's catch your attention!

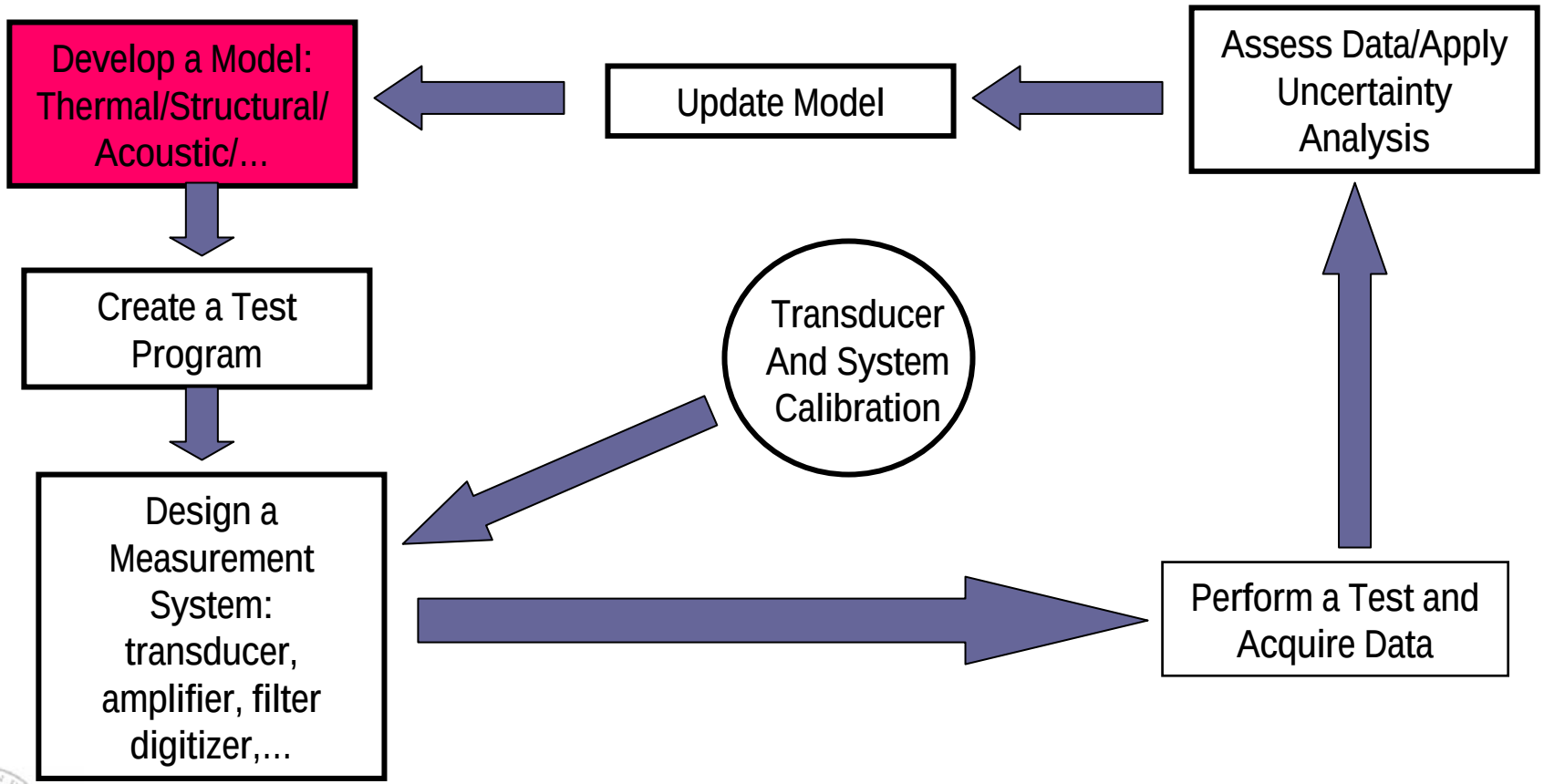


Line of sight pipe

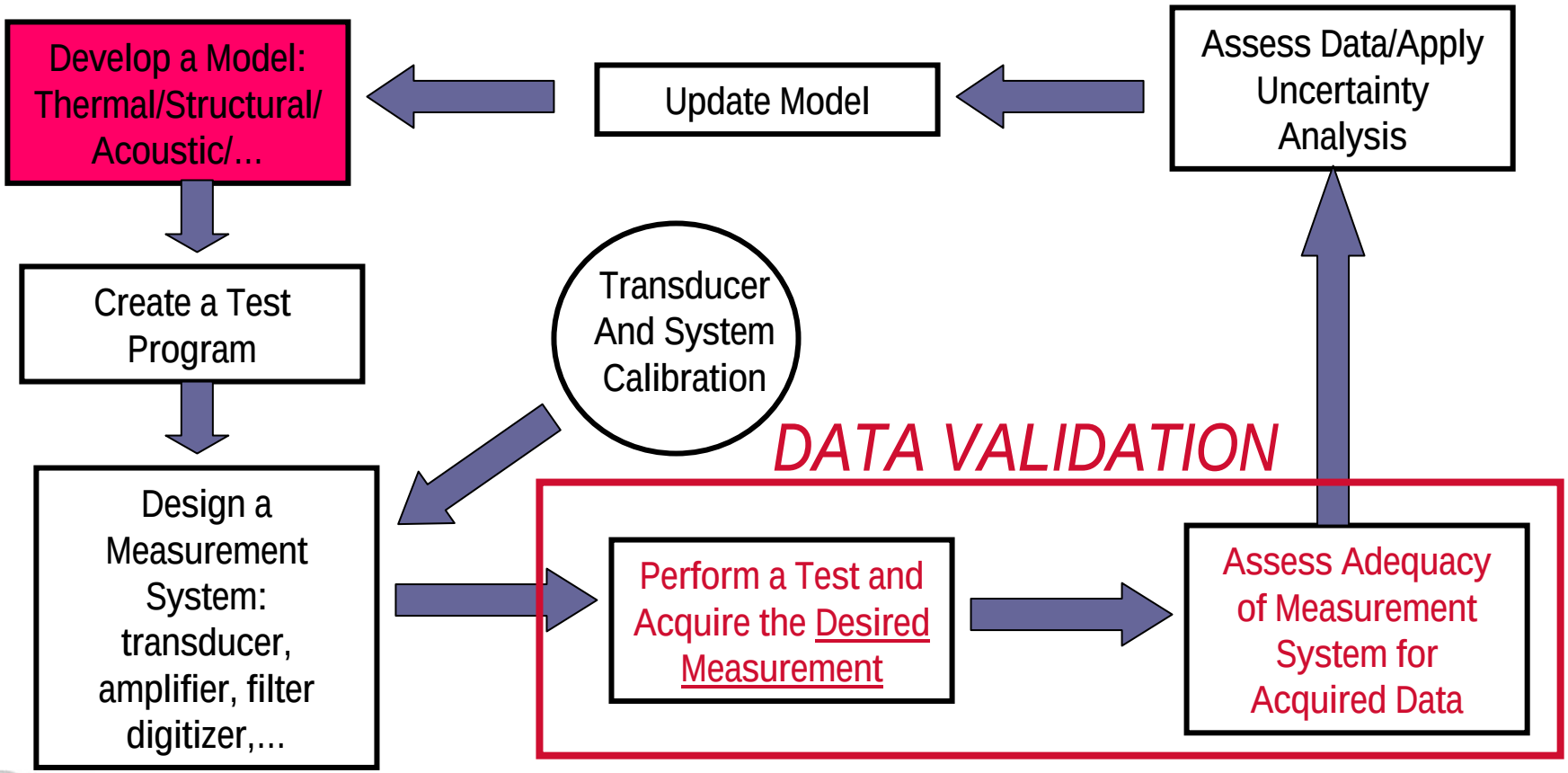


Olsen, Strain Sensitivity of Pressure Transducers in a Dynamic Environment, 8th Transducer Workshop

The Typical Design, Analysis, and Test Cycle



What's Missing From the Preceding Design, Analysis, and Test Cycle?



Should ACCURACY or VALIDITY be the first concern?

In some situations the discussion changes from how accurate are the data to do the data mean anything at all?

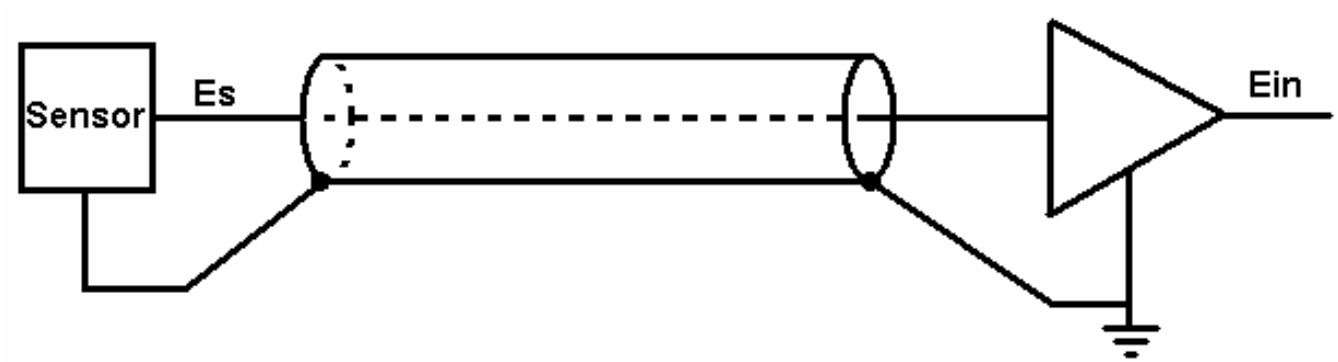
Classical Noise Considerations

- Noise
  - protect against electromagnetic and electrostatic fields and currents coupling through common impedances
    - electromagnetic: time-varying magnetic fields (solenoids, motors, power transformers)
      - shield by completely enclosing the susceptible circuit (use high permeable material such as Permalloy)*
    - electrostatic: time-varying potential difference between two conductors coupled by stray capacitance
      - shield with stranded braid mesh and screens of good electrical conductors*

**Good magnetic shields are relatively good electrostatic shields but the converse is not true.*

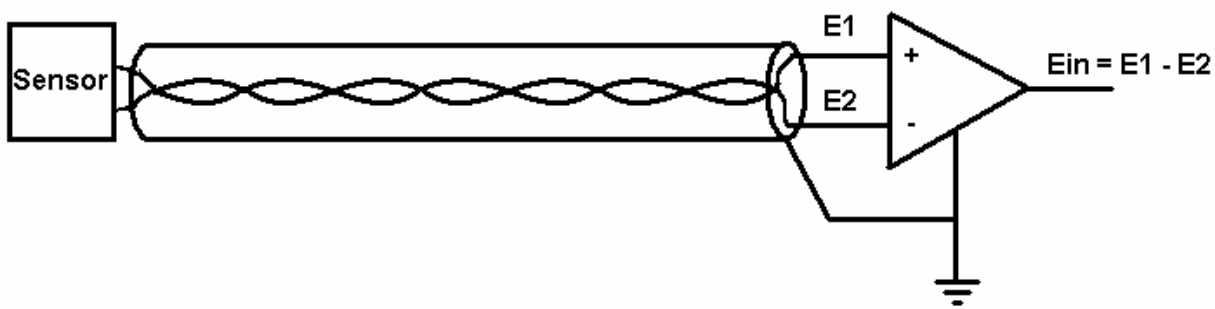
Classical Noise Considerations

- current coupled: signal currents share a common path with other undesired currents
  - provide a single ground
  - keep cables short



Classical Noise Considerations

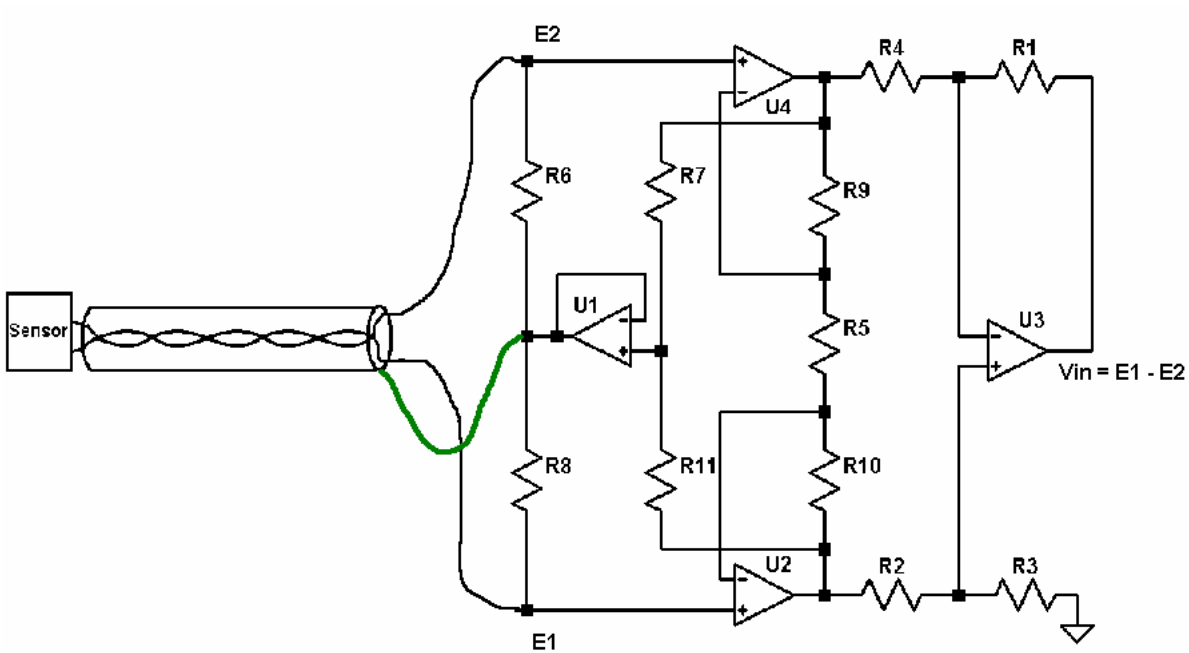
- Grounding considerations:



- Twisted/Shielded pair most commonly used cable for differential inputs.
- Shield may be separated from the signal path, reducing noise coupling to the input.

Classical Noise Considerations

- Grounding considerations:

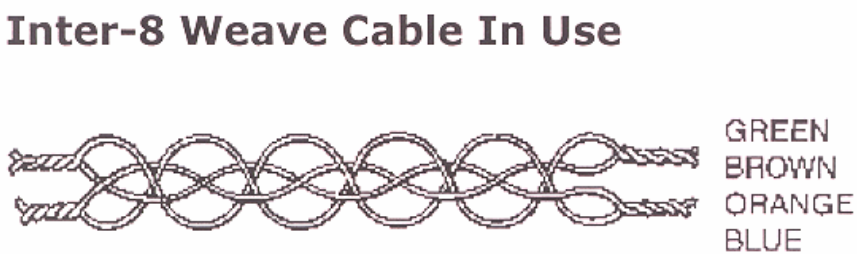


  - If the shield is driven, the loading effect of the different capacitors will no longer exist

Classical Noise Considerations

Permalloy- An 80/20 alloy of nickel and iron; easily magnetized and demagnetized

magnetic shields



Magnetic Shield Corporation
Bensenville, IL
shields@magnetic-shield.com

Measurement System Noise Definition

For our purposes:

Noise is anything but the desired response from a transducer to the desired environment.

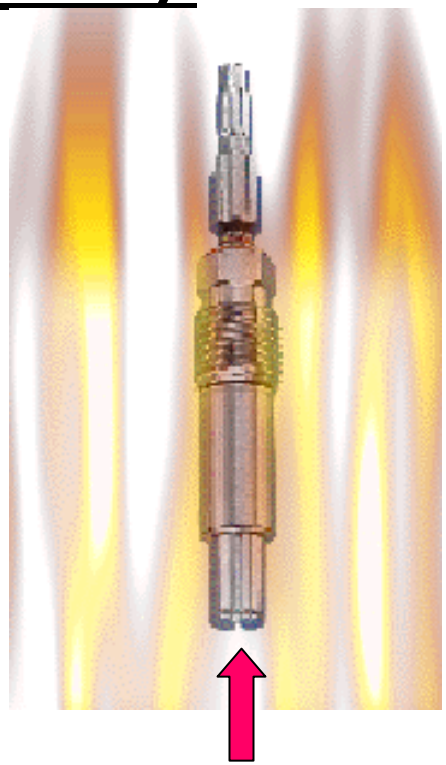
Pressure Transducer Outputs are Combinations of Responses to Environments

FROM ISA 37.10 (PIEZOELECTRIC PRESSURE TRANSDUCERS):

& ACCELERATION!

STEADY STATE TEMPERATURE

AMBIENT PRESSURE



TRANSIENT TEMPERATURE

CABLE NOISE

ETC.

PRESSURE

Accelerometer Outputs are Combinations of Responses to Environments

FROM ISA 37.2 (PIEZOELECTRIC ACCELEROMETERS) :

& ACOUSTIC PRESSURE!

STEADY STATE TEMPERATURE

HUMIDITY

ACCELERATION!

TRANSIENT TEMPERATURE

NUCLEAR RADIATION

RFI

ACCELERATION

ELECTROMAGNETIC INTERFERENCE

ETC.

Environmental Responses

Testing is preferred in controlled laboratory conditions. However, these controlled laboratory conditions are not always available.

acceleration desired

Sandia Labs

modal testing:
temperature, humidity, rfi, base strain, …

Environmental Responses

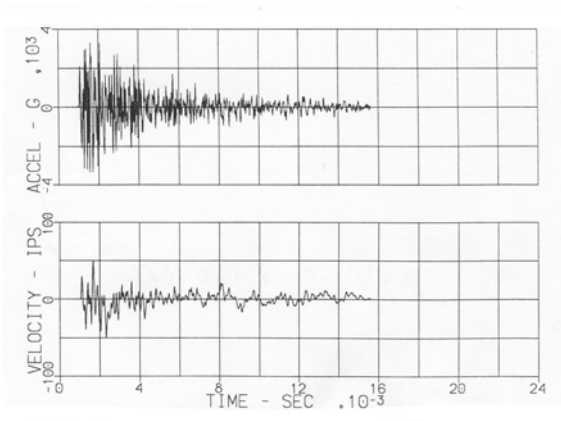
Testing is preferred in controlled laboratory conditions. However, these controlled laboratory conditions are not always available.

pressure desired

Sandia Labs

shock tube: thermal transient, ionized gases, strain, moisture, pickup on long lines, …

Answers Needed to Validate Data: One Example



Assume:

- an uncertainty analysis has been performed and channel error bounds assigned
- and, the latest micro-P controlled DAQ has ideally digitized the acceleration record shown to megabits resolution at a sample rate approaching infinity and it somehow gets transmitted to the ground.

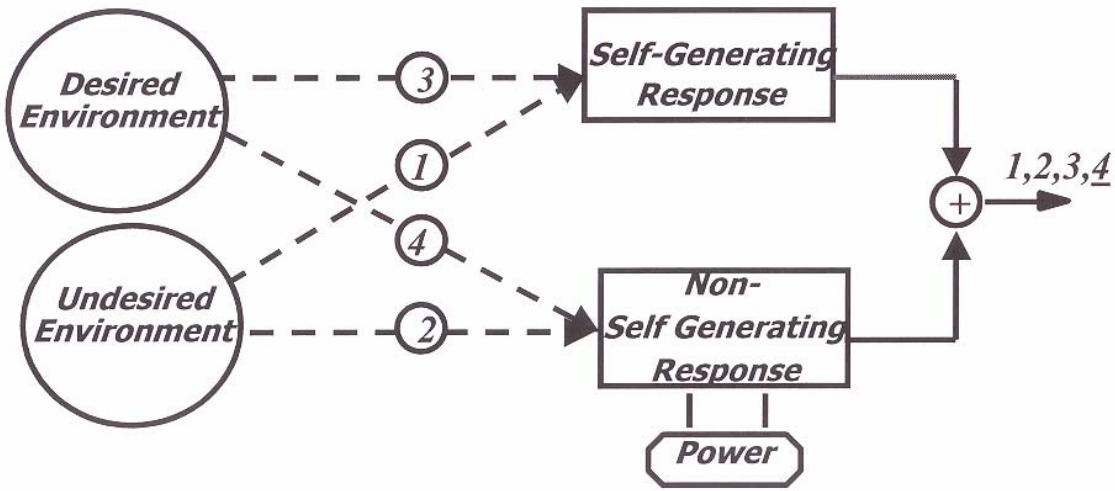
These questions remain:

1) Is the transducer responding only to its desired environment or are the data contaminated by other environments?
2) Is the signal frequency content compatible with the recording capability of the data acquisition system?

Deal with Question #1: Is the transducer responding only to its <u>Desired Environment</u>?

Non-self Generating Transducer Model (Impedance Based ΔL, ΔC, ΔR)

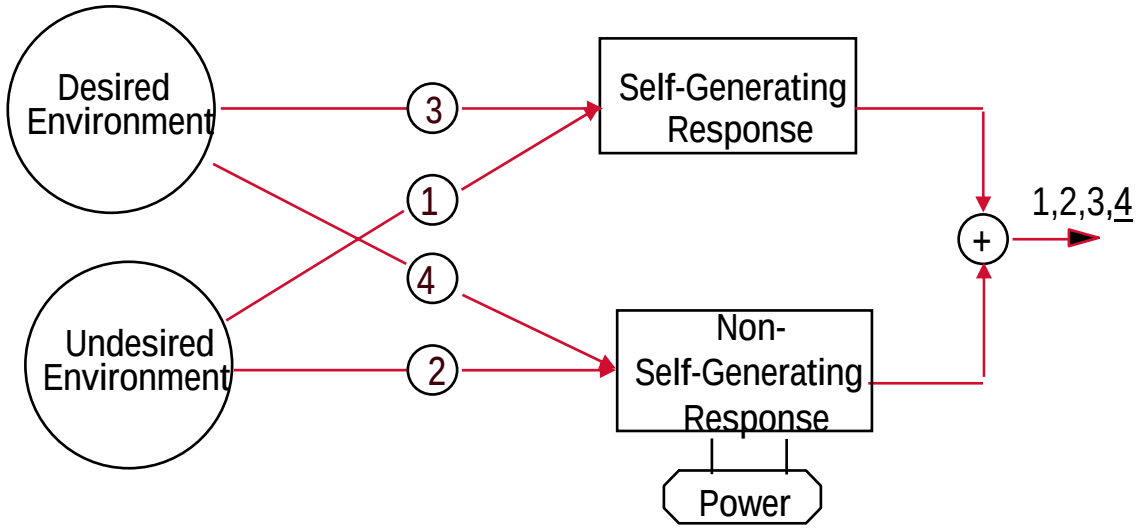
Response Type	*Environmental Input*
Non-self generating	*Desired*
Self-generating	*Undesired*



What Comprises Data Validation? (Example #1)

Bridge Type Accelerometer (e.g. acceleration [desired] and temperature [undesired] responses)

Ref. Stein, ISBN 1-881472-00-0



path 4: signal
path 1: thermoelectric (noise)
path 2: thermoresistive (noise)
path 3: piezoelectric (noise)

kill power (field unpowered accelerometer)	→ paths 1,3
remove desired environment (field isolated accelerometer)	→ paths 1,2
field hard mounted and powered accelerometer	→ paths 1,2,3,4

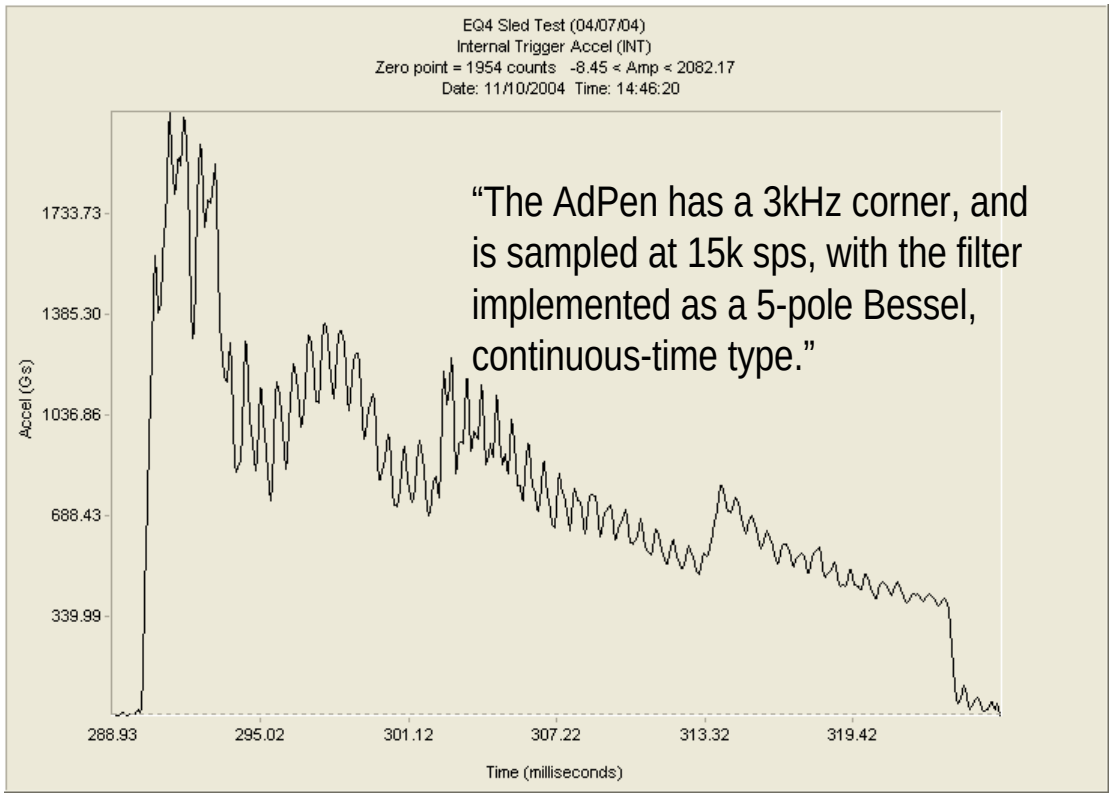
What Comprises Data Validation? (Example #1)

The following example was provided by Mike Partridge, Senior Member of the Technical Staff, Sandia National Laboratories, on November 16, 2004. Mike graciously sponsored a course at Sandia under TCU's Extended Ed Department in May 2004. Mike designs and builds data recording systems for penetrators. The AdPen is a legacy system and the AdPen-NV a developmental system. Mike's quotes follow:

"The AdPen-NV and AdPen were used in two separate tests, but with very similar test conditions. Both were fired in a 71-pound penetrator from a gas gun into 6 ksi reinforced concrete (since the targets were so old, the assumption is that the concrete was closer to 7ksi).
We only have launch data for both tests."

What Comprises Data Validation? (Example #1)

Legacy System:



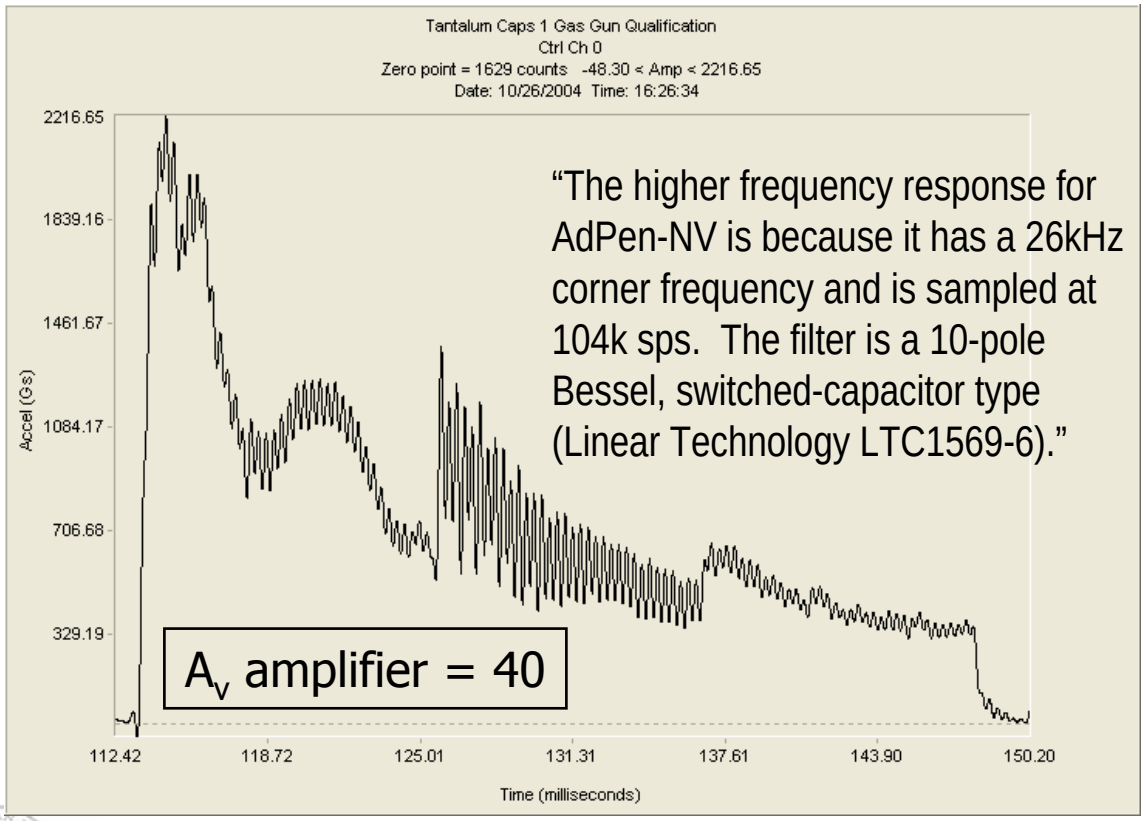
"The AdPen has a 3kHz corner, and is sampled at 15k sps, with the filter implemented as a 5-pole Bessel, continuous-time type."

Why do we believe it?

"we have done experiments on a rocket rail where we could confirm measurements using external instrumentation cabled to the unit. Second, dummy channels on it show 0.1 mV or less at impact."

What Comprises Data Validation? (Example #1)

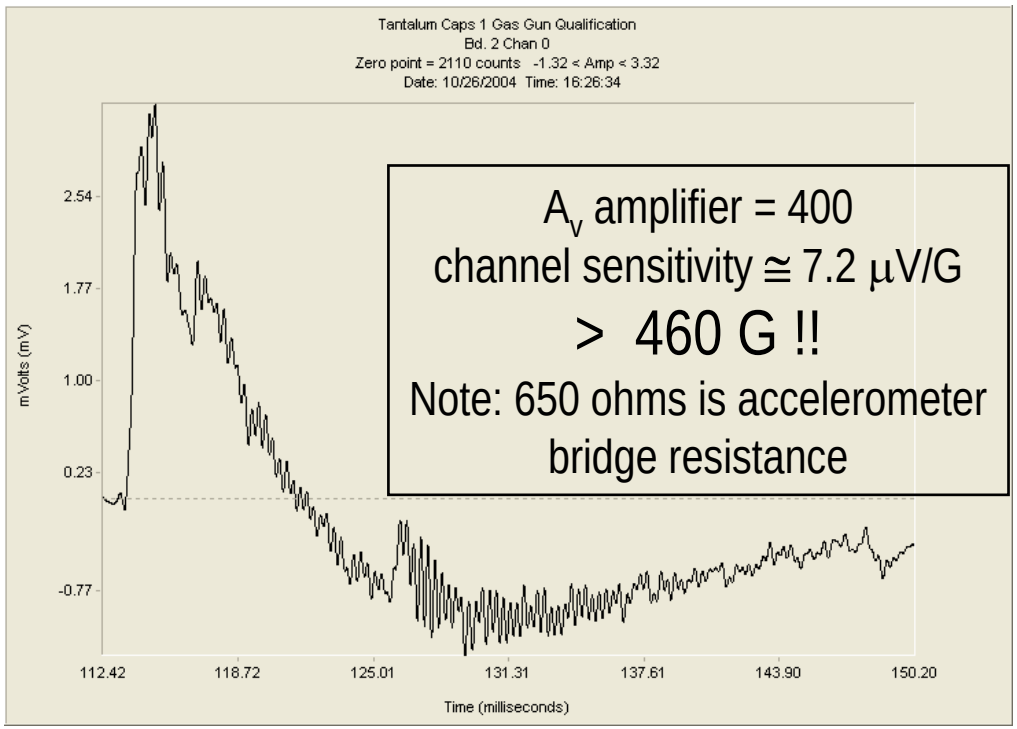
New AdPen-NV Data Recorder



Should <u>we believe it?</u>

What Comprises Data Validation? (Example #1)

AdPen-NV Recorder; 650 Ohm R_{input} Dummy Channel

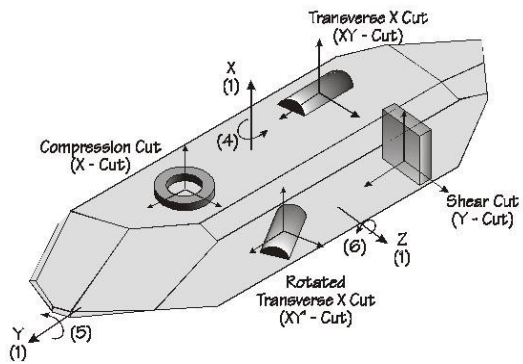


The answer is NO!

"Our analysis so far based on the flight tests plus additional shock lab tests is that we are seeing a piezoelectric effect in the signal conditioning circuitry ceramic capacitors, plus possibly something similar at high energy levels (>2000G for 10's of milliseconds) in integrated circuits with internal capacitors (in this instance, a switched-capacitor filter)."

Self Generating Piezoelectric Type Transducer Noise Validation

Quartz Boule



Poling Ceramics

$$P_{xx} = d_{11}\sigma_{xx} - d_{11}\sigma_{yy} + 0\,\sigma_{zz} + d_{14}\tau_{yz} + 0\,\tau_{zx} + 0\,\tau_{xy}$$
$$P_{yy} = 0\,\sigma_{xx} + 0\,\sigma_{yy} + 0\,\sigma_{zz} + 0\,\tau_{yz} - d_{14}\tau_{zx} - 2d_{11}\tau_{xy}$$
$$P_{zz} = 0\,\sigma_{xx} + 0\,\sigma_{yy} + 0\,\sigma_{zz} + 0\,\tau_{yz} + 0\,\tau_{zx} + 0\,\tau_{xy}$$

where a "P" is a piezoelectric directional constant, a "d" is a piezoelectric coefficient, and a "σ" is a stress component

Random Vibration Measurement (Example #2)

Statement of Problem:

In the B61, it was desired to measure random vibration to determine its effect on a switch concurrent with parachute deployment. Testing was to be performed on a sled track. Data acquisition would be by RF telemetry.

Anticipated environments:

Acceleration pulse: 150 G, spectral content to 50 Hz
Random vibration: +/- 10 G

Random Vibration Measurement (Example #2)

Instrumentation:

(8 ea) Airborne charge amplifiers
-3 dB point @ 2 Hz
(8 ea) Piezoelectric accelerometers
6 active and 2 depolarized
(8 ea) VCOs
(2 ea) RF transmitters at 239.4 & 248.6 MHz
(3 active accelerometers & 1 noise monitor/transmitter)

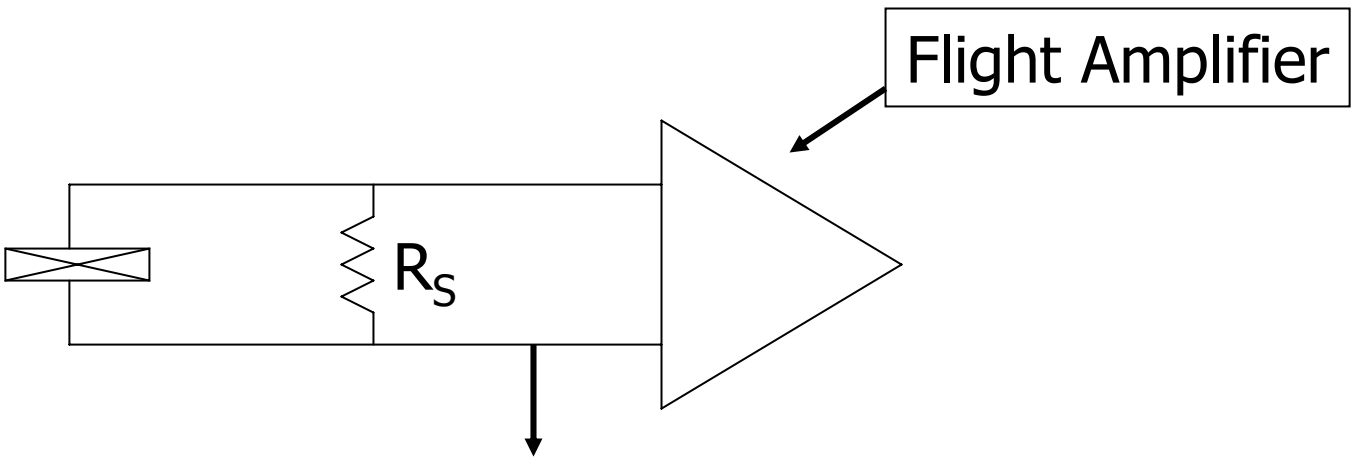
Random Vibration Measurement (Example #2)

The challenge was to eliminate the effects of the 150 G parachute pulse from the data to enable adequate amplitude resolution to resolve the anticipated +/- 10 G random vibration. Otherwise, the parachute pulse would saturate the channels.

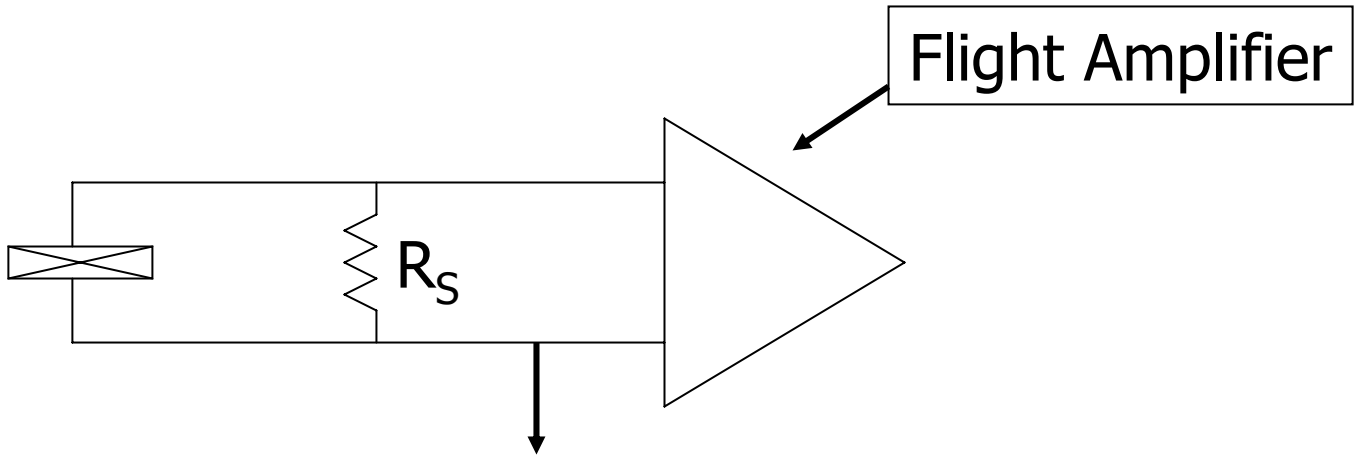
The proposed solution follows.

Random Vibration Measurement (Example #2)

The low frequency –3 dB point of the amplifiers was moved to 50 Hz by the addition of shunt resistance (R_S). This should effectively filter (high-pass) out the effects of the parachute pulse.



Random Vibration Measurement (Example #2)



Shunt resistance of 6-8KΩ was inserted at a "tee" placed In the coaxial cable of each charge amplifier.

Random Vibration Measurement (Example #2)

Eight (8) systems were used and multiplexed into two (2) groups of four (4) through the VCOs. Each set of four (4) VCOs was put into one of the two (2) transmitters. Each set had 3 active accelerometers and one depolarized accelerometer as inputs.

Complication:

Before parachute deployment a gas generator fired. The effect of this was to saturate all six (6) active accelerometer channels and obscure the event to be recorded. The noise monitor channels also saturated!!!

Random Vibration Measurement (Example #2)

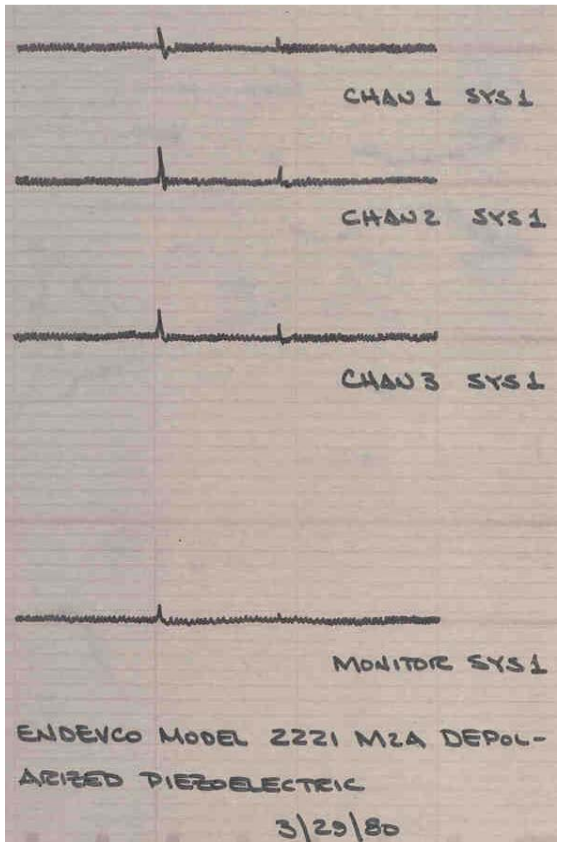
Investigation after the fact:

Post test the 4 accelerometers on the 239.4 MHz transmitter were pulled from the vehicle skin and placed on a metal plate. Hitting the plate with a hammer caused all channels on this transmitter (noise monitor too) to respond. In addition, signals were also coupled into the 246.8 MHz channels!! NO MECHANICAL EXCITATION WAS APPLIED TO THESE??

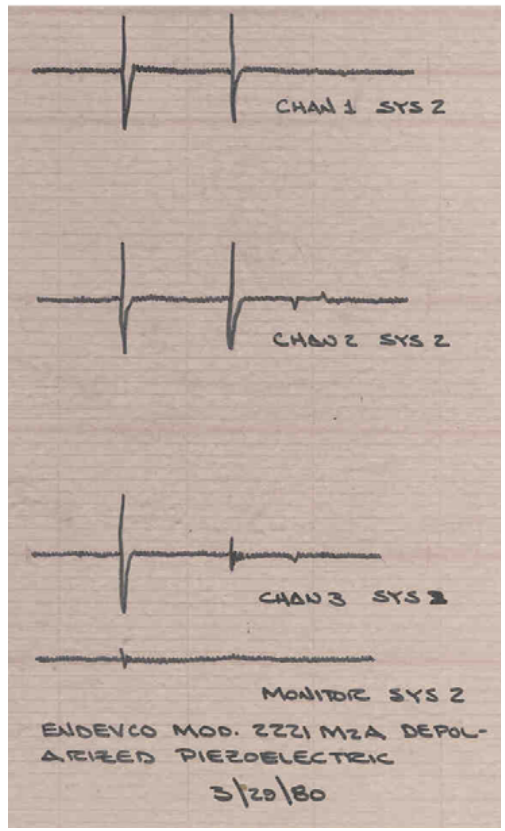
Random Vibration Measurement (Example #2)

Investigation results:

239.4 MHz



248.6 MHz

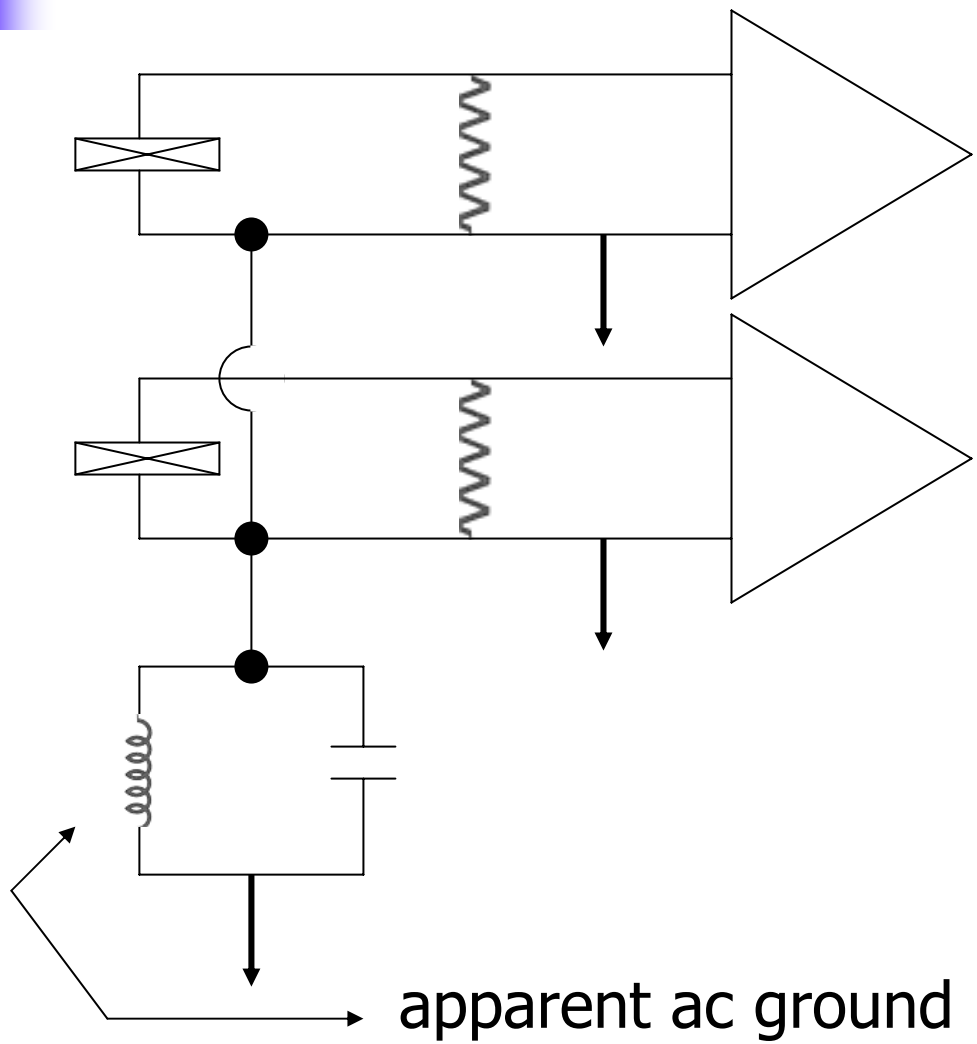


Random Vibration Measurement (Example #2)

WHY?

All of the ”tees” in the cables of the accelerometers to both transmitters had been made common to a metal block to which they were all attached. This block was isolated from ground. When hit with a hammer, or the gas generator fires, the accelerometers ring at their 40 KHz resonant frequencies and an apparent ac ground was formed coupling all eight (8) channels together.

Random Vibration Measurement (Example #2)



Investigation Results

etc. (4 total)

Random Vibration Measurement (Example #2)

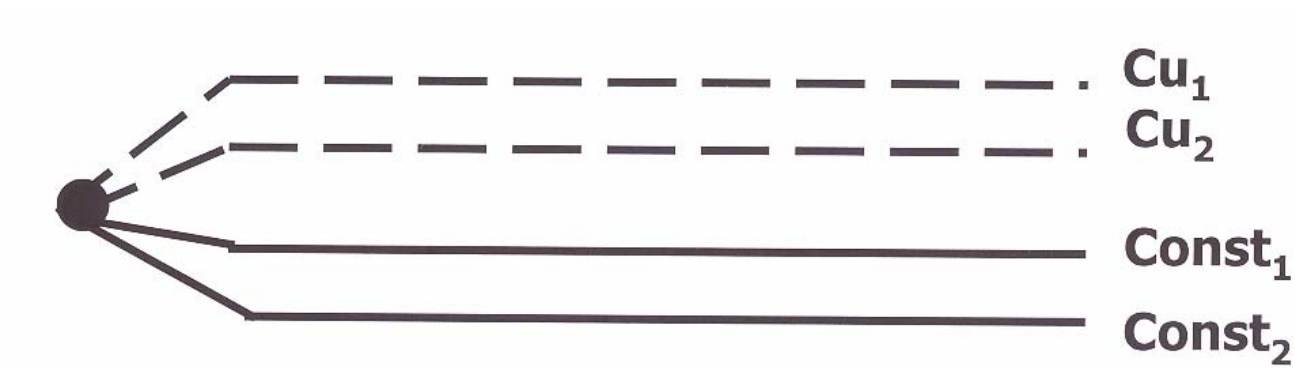
Due to the check channels in flight, bad data were not accepted as good and corrective action could be taken on subsequent flights.

Data Assessment

General:

Assessment of test data can only begin once it is assured by check channels that the data channels are noise free.

Self Generating Thermoelectric Type Transducer Noise Validation



Monitor:

Cu_1-Cu_2: noise

$Const_1$-$Const_2$: noise

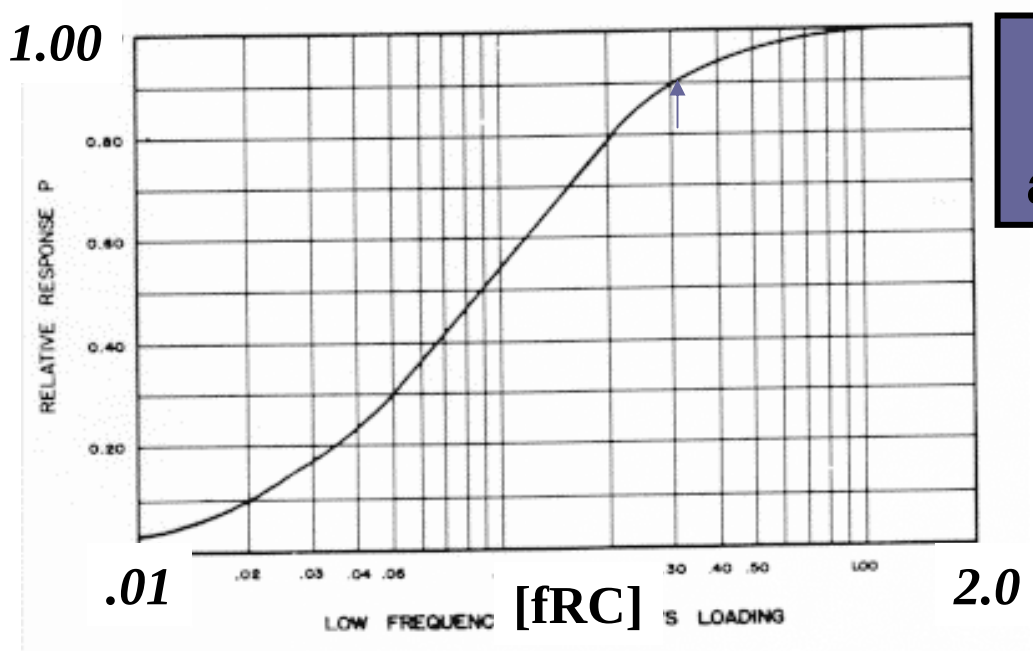
Cu_1-$Const_1$: signal

Cu_2-$Const_2$: signal

Deal with Question #2: Is the recording capability of the Measurement System adequate to have passed the acquired data without distortion?

Data Assessment
Low Frequency Response

- Governed by time constant τ of electronics for piezoelectric transducers. DC or 0 Hz for piezoresistive or silicon-based transducers.
  - Sinusoidal stimulus considerations:

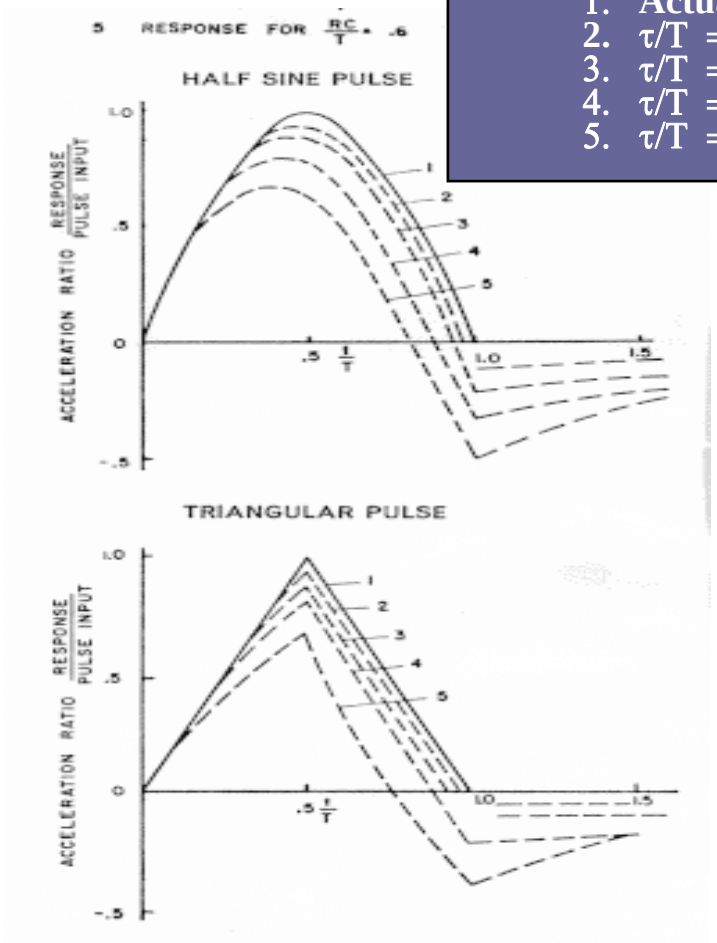


f τ =0.3 @10 % attenuation

Data Assessment
Low Frequency Response

Transient considerations: [A time constant (τ) $\geq$ 10 times the pulse width will allow less than 10% droop at the end of a square wave and guarantee better performance on other pulses (shown right)].

1. **Actual Pulse**
2. τ/T = 6
3. τ/T = 3
4. τ/T = 1.5
5. τ/T = .6

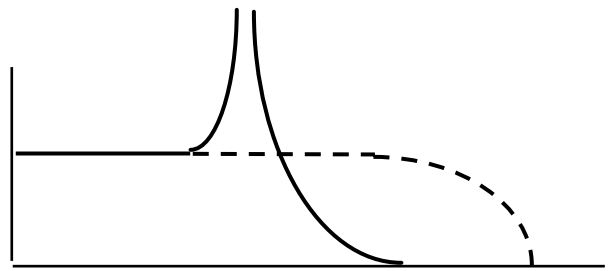


Bickel & Keltner, Sandia Labs, SAND78-0497

Data Assessment
High Frequency Response

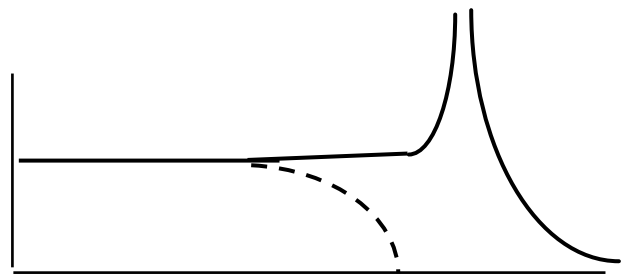
Two cases:

I



transducer limits response

II

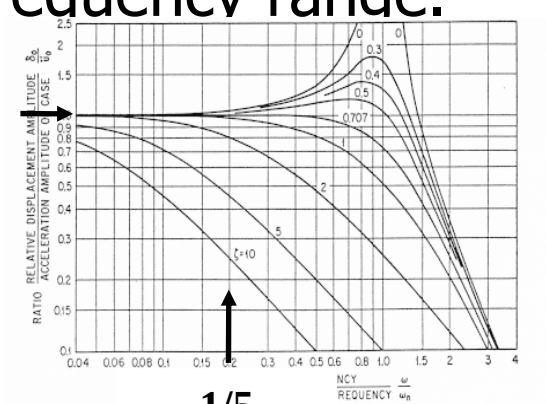


electronics limit response

Data Assessment – High Frequency Response (Assume no Electronic Limitations)

- Governed by lowest resonant frequency of transducer
  - Sinusoidal stimulus considerations
    - An undamped second order system has frequency response flat within 4% to 1/5 its resonant frequency and constant phase shift over this frequency range.

1.04



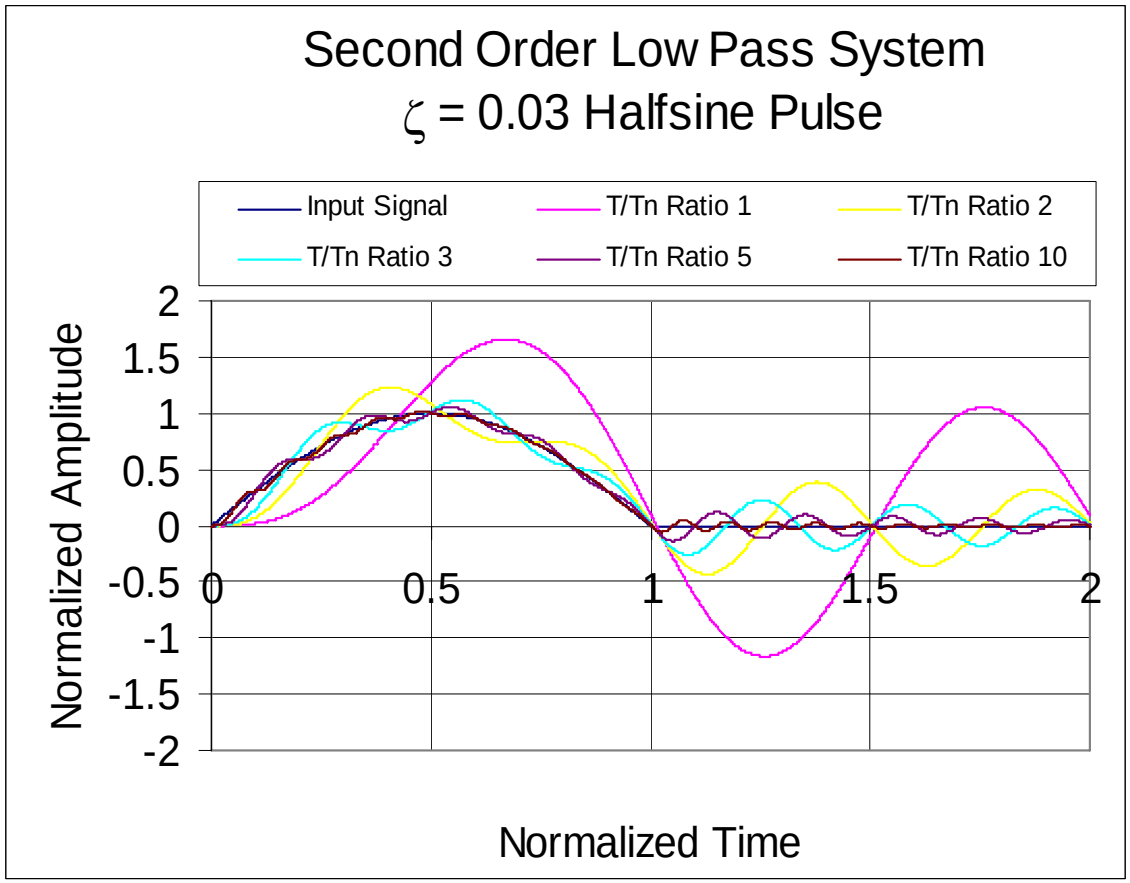
1/5

High Frequency Response (Assume no Electronic Limitations)

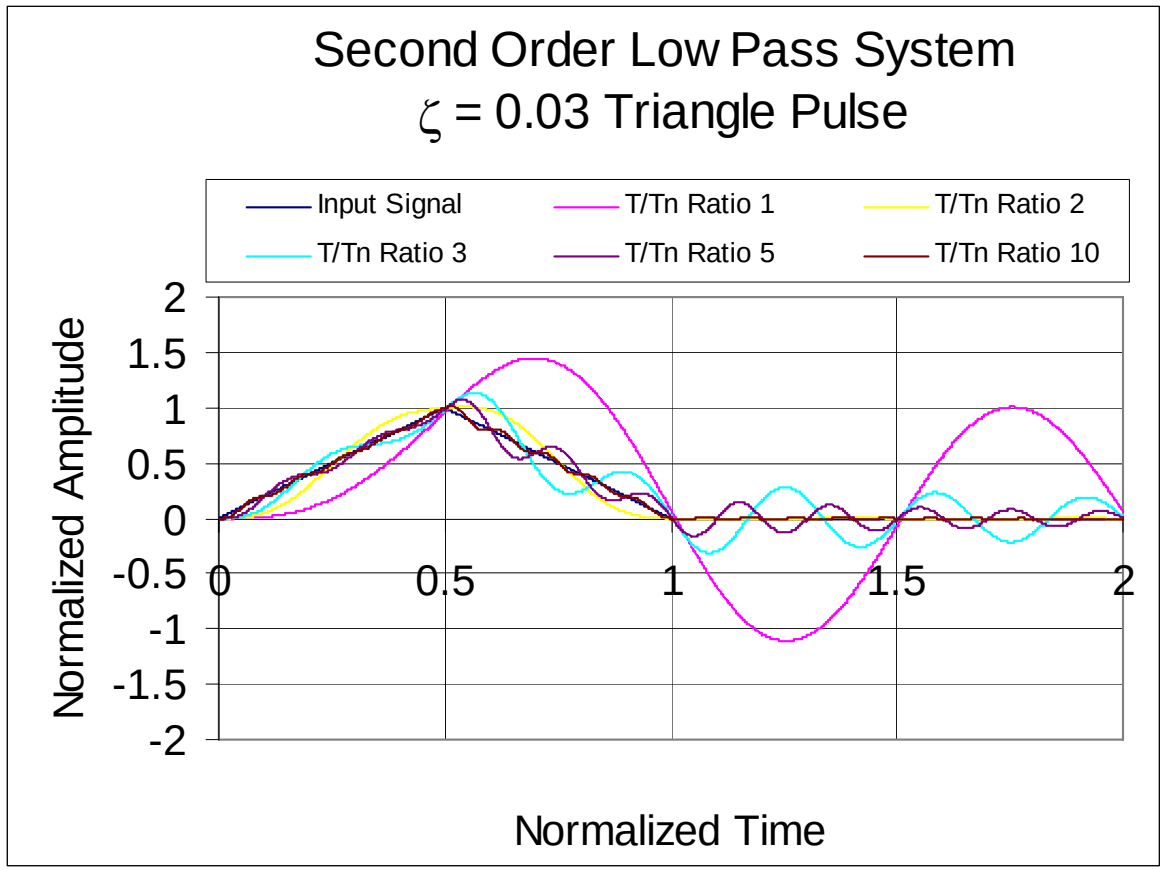
- Transient considerations
  - A pulse duration 5 or greater times the natural period (T_n = 1/[f_n = resonant frequency]) of the transducer will guarantee less than 10% overshoot on pulse peak for any symmetric pulse.
  - For pulses with rise times shorter than fall times, a pulse rise time (t_r) of 2.5 or greater times the natural period (T_n = 1/[f_n = resonant frequency]) of the transducer will guarantee less than 10% overshoot on pulse peak for any pulse.

  **duration is usually measured @ 10% pulse amplitude, rise time is the 10-90% pulse risetime*

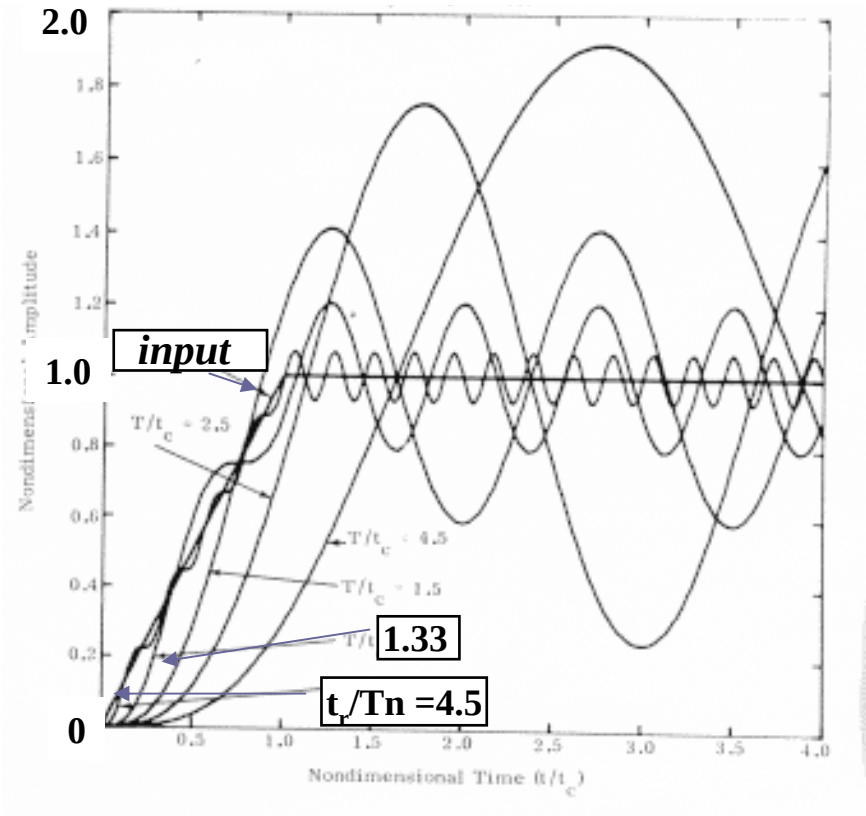
High Frequency Response (Assume no Electronic Limitations)



High Frequency Response (Assume no Electronic Limitations)



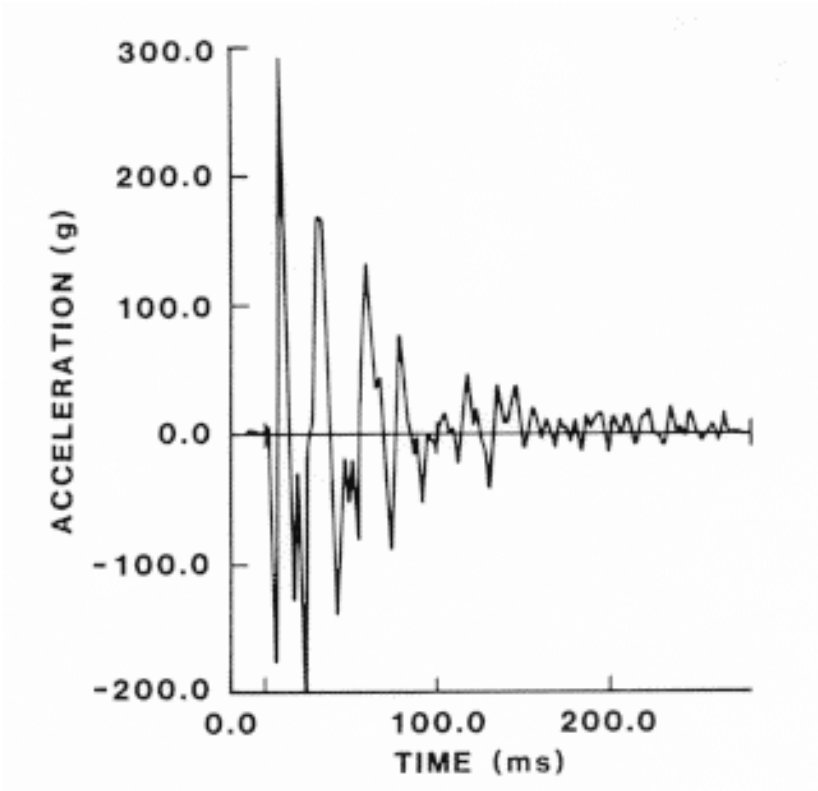
High Frequency Response (Assume no Electronic Limitations)



risetime controls

Bickel & Keltner, Sandia Labs, SAND78-0497

But Test Recordings Can Be Complex



What do we do?

- Low Frequency
  - Look at the time duration associated with the records widest positive or negative going pulse and assure it is no greater than (1/10) $\tilde{\tau}$
  - Look for evidence of bias (undershoot) in the data.

- High Frequency
  - Look at the time duration associated with the record's shortest positive or negative going pulse and assure it is at least 5 T_n.
  - Look at the time duration associated with the record's shortest positive or negative going rise time and assure it is at least 2.5 T_n.
  - Look for evidence of the accelerometer's resonance in the data.

High Frequency Response (Electronic Limitations)

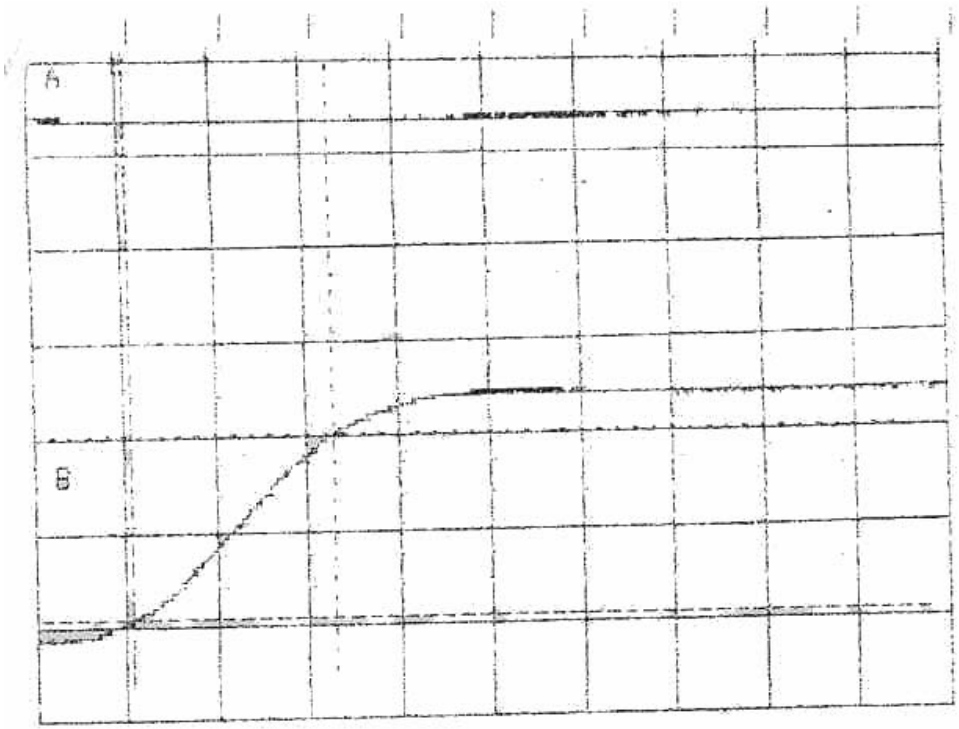
- All measurement systems have some high frequency limitation typically specified by their -3dB or half-power frequency where their response is .707 of that in their "flat" range.

- For any system monotonically decreasing in frequency:

$$t_r f_{-3dB} = .35 \text{ to } .45$$

where t_r is the 10-90% pulse rise time. *A value of $t_r f_{-3dB}$ of say 0.4 would indicate that the rise time and pulse peak are compromised, <0.35 is impossible, & >0.45 indicates that t_r is valid.*

High Frequency Response (Electronic Limitations)



$dv = 3.92V$

$t_r = dt = 232\ \mu s$

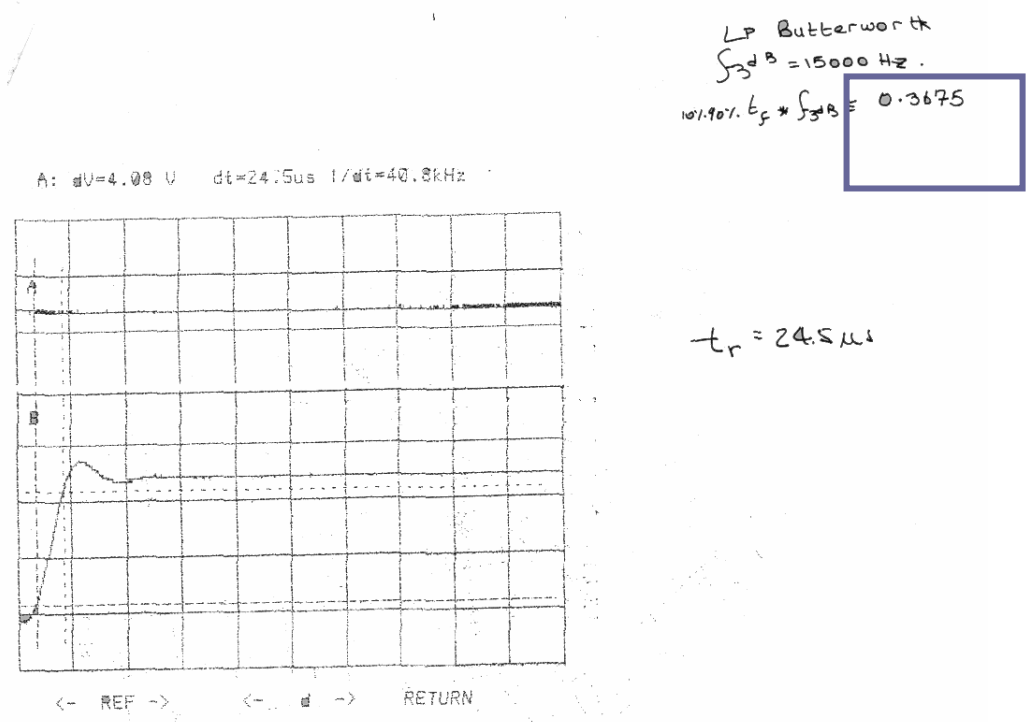
Lp Bessel

$f_{3dB} = 1500\ Hz$

$10\text{-}90\%\ f_{3dB} * t_r = \boxed{0.348}$

Step input (top) to 1,500 Hz –3dB lowpass Bessel filter

High Frequency Response (Electronic Limitations)



Step input (top) to 15,000 Hz –3dB lowpass Butterworth filter

High Frequency Response (Electronic Limitations)

- Example: $t_r f_{-3dB} = .35$ to $.45$
  - A signal is elicited from a pressure transducer with a resonant frequency of 200 KHz. The signal has a 10-90% rise time of 20 μs. The measurement system has a -3dB frequency of 20 KHz. Assume the system operates within its linear range. Is the rise time valid?

- $T_n = 1/f_n = 5\ \mu s$, OK based on pressure transducer since $(t_r/(Tn = 5\ \mu s)) = 4$ which is > 2.5
- now apply $t_r f_{-3dB} = 20\ (10^{-6}) \times 20{,}000 = .4$

Note: .35 < .4 < .45 so rise time is <u>invalid</u>

High Frequency Response (Electronic Limitations)

- The rise time of a measurement system comprised of components which monotonically roll off in frequency is the square root of the rise time of the individual components.

$$t_{sys} = (t_1^2 + t_2^2 + t_3^2 + \ldots)^{1/2}$$

- For safety, the pulse rise time should be greater than 5 times the system rise time.

$$t_r > 5t_{sys}$$

High Frequency Response (Electronic Limitations)

- Example:
  - A force transducer signal with an anticipated rise time of 10 μs is to be passed through a measurement system with these characteristics:
    - amplifier t_r = 2 μs
    - antialiasing filter t_r = 8 μs
    - digital oscilloscope t_r = .5 μs

    Is the system response adequate?

$$(4 + 64 + .25)^{1/2} \sim 8^{+}$$

10 is less than 5 x (8+) μs, No: not adequate

Paper Conclusions

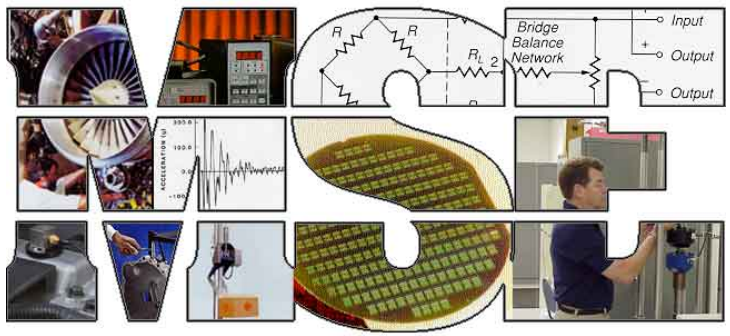
"The preceding material has served to illustrate the data-validation process. It has shown several methods by which to perform data validation and has also shown the value of data-validation in documenting erroneous signals. When measurement systems are required to operate in situations where their environmental boundaries are not fixed, validation channels should always be provided. The final configuration and utility of these channels is limited only by the resourcefulness of the instrumentation engineer. Without the presence of these channels, data accuracy bounds based on uncertainty analysis remain questionable. Also included in this presentation have been simple rules of thumb to allow verification of the adequacy of the measurement system to record the desired transducer response (now validated!) without distortion."

Excerpted From Measurement System Design Program

Successful Measurement of Dynamic Force, Pressure, and Acceleration

A Seminar offered by PCB Piezotronics, Inc.
May 16 – 18, 2006 • Buffalo, NY

1 ½ days focused with additional plant tour



Measurement System Engineering

3 days customer on-site program via TCU Extended Ed and Dept. of Engineering