Dynamic Pressure Calibration

Based on ISA-37.16.01-2002
"A Guide for the Dynamic Calibration of Pressure Transducers"

Introduction to the Tutorial

- Tutorial based on ISA S37.16.01
  A Guide for the Dynamic Calibration of Pressure Transducers 2002
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- Section & Figure references are from the Standard

Instructor

- Jon Wilson, Principal Consultant
  The Dynamic Consultant, LLC
  - Over 45 years in testing and instrumentation Test Engineer, Lab Manager, Applications Engineering Manager, Marketing Manager, Consultant & Lecturer (since 1985)
  - Chrysler Corp., ITT Cannon Electric, Motorola, Endevco, The Dynamic Consultant
  - ISA SP37 Committee Member

History

- Originally ASME Standard
- ANSI Std. since 1972
- ASME > ISA in 1996
- 1997 ISA SP37.16 Subcommittee on Pressure Transducers began update
- Result: ISA-S37.16 A Guide for the Dynamic Calibration of Pressure Transducers

Contributors

- Some people here were major contributors

- Any Working Group members present, please stand and be recognized

Introduction to the Standard

- Need to measure rapidly changing pressures
- First need to characterize the transducer
- Recent advances in dynamic pressure generators
- Recent advances in data acquisition have improved accuracy and frequency range

Intent of S37.16

- Document current techniques
- Identify possible pitfalls
- Improve communication in the field
- Not a step-by-step procedure
- Not discussion of all factors affecting pressure measurement
- Concentrates on what affects dynamic response

What's in it?

- Scope, Purpose, Table of Symbols
- Transducer properties, dynamic pressure sources, use of pressure sources
- Problems of transducer installation, electronic signal conditioning
- Data recording methods, recommended reporting procedures

Section 1, Scope

- Establishes minimum specifications for design and performance characteristics for pressure transducers; uniform acceptance and qualification tests, including calibration techniques and test conditions; and drawing symbols for use in electrical schematics.

Section 2, Purpose

- Establishes guidelines for calibration of dynamic pressure transducers
- Covers pressure transducers, primarily those used in measurement systems
- Applies to absolute, differential, gage and sealed reference transducers

Section 3, Symbols

- Terminology and symbols are consistent with ISA SP51.1, SP37.1 and IEEE "Dictionary of Standards"

Table of Symbols

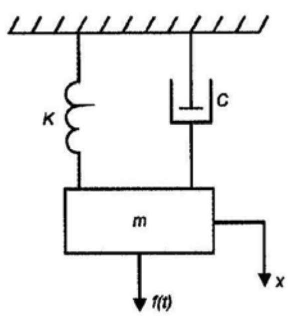
3 Table of symbols

a	gas speed of sound	RC	time constant of R-C circuit
A_e	outlet orifice area	t_s	settling time
$\hat{A}_e$	maximum exit area	Δt_s	shock-wave transit time
A_i	inlet orifice area	t_r	rise time, transducer
A_r	amplification factor	T	temperature
c	damping	v	chamber volume
d	diameter	V	voltage or volume
f	frequency	ΔV	peak incremental voltage
k	spring constant	$\hat{V}$	peak voltage for any cycle
K	steady-state sensitivity	$\overline{V}$	average voltage
l	piston position	V_p	peak-output voltage
L	length of cylindrical passage	V_s	shock-wave velocity
m	mass	$\propto$	modulation factor
M_s	shock wave Mach number	γ	ratio of specific heats of constant pressure and volume
N	number of oscillations		
$\frac{OUT(s)}{IN(s)}$	transfer function	η	constant
p	pressure	ζ	damping ratio
p_s	stagnation pressure of supply gas	λ	wavelength
p_a	absolute pressure	τ	rise time, input
ΔP	pressure change	ω	frequency in radians per second
p_o	equilibrium pressure	ω_d	ringing frequency
$\overline{p}$	average chamber pressure	ω_o	natural frequency
		ω_r	resonant frequency

4, TRANSDUCER PROPERTIES

- Transfer function > Frequency response
- Assumed:
  - Linear
  - Second order
  - Single degree of freedom

4.1, Underdamped Second-Order



(Eq. 4.1) $$\frac{d^2x}{dt^2}+\frac{c}{m}\frac{dx}{dt}+\frac{kx}{m}=\frac{f(t)}{m}$$

Transfer Function

(Eq. 4.2) $$\frac{OUT(s)}{IN(s)} = \frac{K\omega_o^2}{s^2 + 2\zeta\omega_o s + \omega_o^2}$$

where OUT(s) is the Laplace Transform of the output,
IN(s) is the Laplace Transform of the input,
K is the steady-state sensitivity,
ω_o is the natural frequency of the system in radians per second = $\sqrt{\frac{k}{m}}$.
s is the complex variable = j (2πf) where f is frequency
ζ is the damping ratio (ratio of actual damping to critical damping)

PE Transfer Function

- PE cannot respond to static pressure
- Add high-pass RC to transfer function

(Eq. 4.3) $$\frac{OUT(s)}{IN(s)} = \frac{K\omega_o^2}{s^2 + 2\zeta\omega_o s + \omega_o^2} \cdot \frac{s}{s + 1/RC}$$

Now when s = 0, the response is zero.

Output Response to Step

(Eq. 4.4) $$e(t) = A\left[1 - \frac{1}{\sqrt{1-\zeta^2}}\, e^{\left(\frac{\zeta \omega_d t}{\sqrt{1-\zeta^2}}\right)} \sin\left(\omega_d t + \arctan\frac{\sqrt{1-\zeta^2}}{\zeta}\right)\right]$$

where $\omega_d = \omega_o \sqrt{1-\zeta^2}$.

- Figure 3 plots Equation 4.4 for various ζ

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Effect of Damping, 1

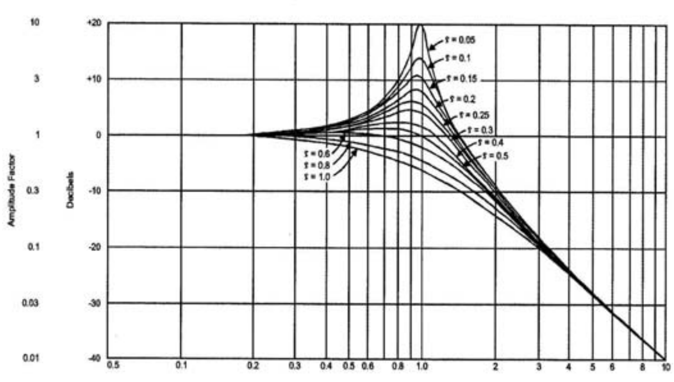

Figure 1 — Amplitude response for an ideal second-order system

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Effect of Damping, 2

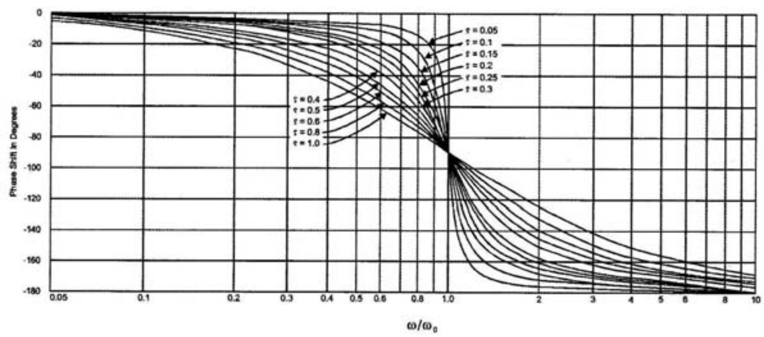

Figure 2 — Phase response for an ideal second-order system

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Transient Response

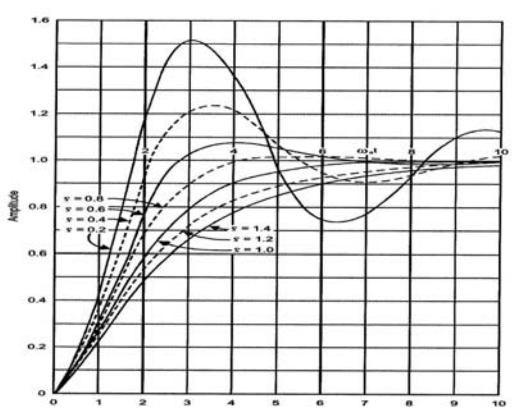

Figure 3 — Response of ideal second-order system to step input of unit amplitude

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4.2, General Transducer Properties

- Many properties relating to static pressure measurement are typically provided by manufacturers.
- This section discusses those with specific application to dynamic measurement.

4.2.1, Sensitivity

- Ratio of output change to input change
  - Usually voltage per pressure unit
- Represented by constant K of Equations 4.2 & 4.3
- If 4.2 (steady state capable), can be established by static measurements
- If 4.3 (no steady state output), dynamic measurement is required

4.2.2, Linearity

- The closeness of a calibration curve to a specified straight line
- CAVEAT: Reference line must be unambiguously specified
- Any deviation from a straight line is a non-linearity
- Usually expressed as % of full scale output

4.2.3, Range

- Measurand values over which a transducer is intended to measure
- Specified by upper and lower limits
- Lower limit usually determined by noise
- Upper limit may be determined by excess non-linearity or by mechanical or electrical clipping

4.2.4, Creep (Drift)

- Change in output over a specific time
  - Measurand held constant
  - Environmental conditions held constant
  - Excitation (if any) held constant
- Usually expressed as % of full scale output per unit time at specified conditions

4.2.5, Hysteresis

- Maximum difference in output, at any measurand value within the range, when the value is approached first with increasing then with decreasing measurand
- Usually expressed as % of full scale output

4.2.6, Proof Pressure

- Pressure that may be applied to the sensing element of a transducer without changing the transducer performance beyond specified tolerances

4.2.7, Repeatability

- Maximum difference in output at the same measurand value applied consecutively under the same conditions and in the same direction
- Usually expressed as % of full scale output

4.2.8, Acceleration Compensation

- Integral accelerometer element that reduces the transducer's sensitivity to motion
- Usually expressed as equivalent applied pressure per g or m/s^2

4.2.9, Thermal Sensitivity Shift

- Change in sensitivity of transducer as a result of a change in steady-state operating temperature
- Usually specified as % per degree C or degree F

4.2.10, Resolution

- Smallest discernible signal
- May be referred to as “threshold”
- May be specified in measurand units
  - psi, Pascal, etc.

4.2.11, Noise

- Any signal in the measurement system other than the desired pressure response
- May be specified in electrical units or equivalent pressure units

4.3, Properties in Frequency Domain

- Properties in the frequency domain are described by the transfer function
  Ref. Eq. 4.2 and 4.3

4.3.1, Amplitude Response

- Frequency response (transfer function) can be computed from Eq. 4.2 or 4.3 by substituting jω for s and computing magnitude
- Figure 1 is a normalized plot that shows deviations from flat response
- Frequency response plot indicates resonant frequencies, bandwidth and damping

4.3.2, Phase Response

- Phase of transfer function vs frequency
- Substitute jω for s and compute phase as ω varies
- Figure 2 is an example of phase response plots
- In time domain, phase indicates instantaneous shape of response and contributes to time lag of response

4.3.3, Resonant Frequency

- Measurand frequency that gives maximum output amplitude
- Lowest frequency resonance usually most important; may be many
- Second order system approximation is usually valid (if first resonance is dominant)
- Amplitude response determined by damping

4.4, Properties in Time Domain

- Descriptions of the transducer response to a specified input, usually a step function

4.4.1, Ringing Frequency

- Sometimes referred to as "damped natural frequency"
- Frequency of free oscillation when excited by step function
- Related to resonant frequency by:

$$\omega_d = \sqrt{\frac{1-\zeta^2}{1-2\zeta^2}}\,\omega_r \qquad \text{(Eq. 4.5)}$$

4.4.2, Damping

- Energy dissipation that, with natural frequency, determines frequency response and transient response characteristics of transducer
- After step-change, underdamped oscillates decaying to final steady value, overdamped does not overshoot, critically damped returns to steady state fastest

4.4.3, Damping Ratio

- Ratio of actual to critical damping, ζ
- Dynamic pressure transducers have very low damping
  - Natural frequency and ringing frequency approximately equal
- ζ determines overshoot and ringing as well as maximum response at resonance, Q

4.4.4, Rise Time

- Time for output to rise from 10% to 90% of its final value in response to step change of measurand
- Rise time is related to transducer frequency response

4.4.5, Overshoot

- Amount of output measured beyond final steady output value in response to step change of measurand
- Maximum theoretical overshoot of ideal second-order transducer is 100% when ζ is zero

(Eq. 4.6) $$\text{overshoot} = 100e^{-\left(\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)}$$

for the condition $\zeta \leq 0.1$.

4.4.6, Settling Time (1)

- Time required, after step-change of measurand, for output to settle within a small specified percentage (usually 5%) of its final value; with small ζ:

(Eq. 4.7) $$t_s = \frac{3\sqrt{1-\zeta^2}}{\zeta\omega_d}$$

4.4.6, Settling Time (2)

- Number of oscillations to settle within 5% for ideal second-order transducer:

(Eq. 4.8) $$N = \frac{3\sqrt{1-\zeta^2}}{2\pi\zeta}$$

4.4.7, Discharge Time Constant

- Time for transducer to discharge its signal to 37% of original value after step-change measurand
- Equivalent to discharge time constant of an R-C circuit
- Relates to low frequency capability for both transient and continuous measurements

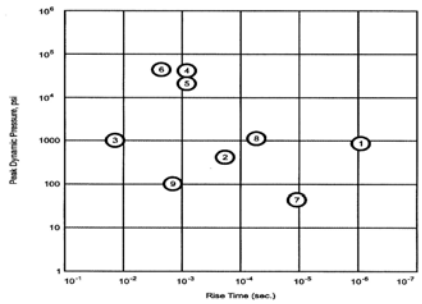
5, DYNAMIC PRESSURE GENERATORS

- Two basic classes: periodic and aperiodic
- Periodic are most often sine-wave generators
  - Limited amplitude and frequency
  - Need transfer standard
- Aperiodic generate a pulse or a step
  - Large variation in amplitudes and rise times

Aperiodic Pressure Generators

The time required for the pressure on the transducer to change from P_1 to P_2 ($P_2 = P_1 + \Delta P$) is given by the expression

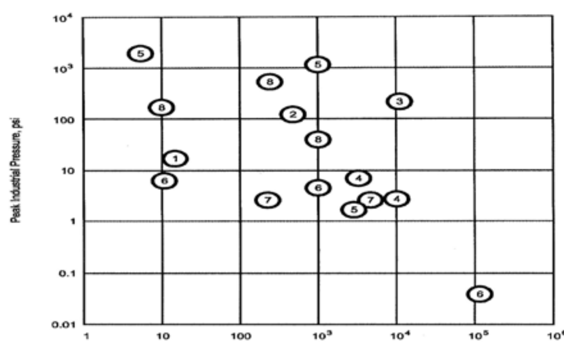
(Eq. 5.3) $t = \frac{d}{V_s}$



1 Shock Tube (gas)
2 Burst Diaphragm (gas)
3 Eiselle Valve (gas)
4 NBS Valve (liquid)
5 DPG Rathke (liquid)
6 NOL Bomb (gas)
7 MEC Swat (gas)
8 NOL PPG (gas)
9 PPU, Suffield (gas)

Figure 4 — Aperiodic generators

Periodic Pressure Generators



1 Rotating Valve (gas)
2 Electrodynamic Pistonphone (liquid)
3 Piezoelectric (liquid)
4 Variable Mass (gas)
5 Hydraulic Pistonphone (liquid)
6 Fluidic Pressure Generator (gas)
7 Resonant, Variable Frequency (gas)
8 Inertial Piston (liquid)

Figure 5 — Periodic generators

5.1, Shock Tubes (1)

- Two sections of tubing separated by diaphragm, different pressures in each section
- When diaphragm is suddenly ruptured, a shock wave is formed in the lower pressure section of the tube
- 10-15 diameters down the tube, shock wave creates positive pressure step

5.1, Shock Tubes (2)

- Characteristics of shock wave depend on tube dimensions, temperature, initial pressure, gas used, initial pressures, etc.
- Amplitude of pressure step depends on: shock wave velocity and initial absolute pressure and temperature in low pressure section

5.1.1, Sidewall Transducer Mounting

- Transducer mounted flush in sidewall of low pressure section will measure "incident" pressure when shock wave passes it
- Using air as the gas in the low pressure section, pressure amplitude can be computed from Rankine-Hugoniot relations

5.1.1, Rankine-Hugoniot Equations

(Eq. 5.1) $$\Delta P = \frac{7}{6} P_1 \left(M_s^2 - 1\right)$$

and

(Eq. 5.2) $$M_s = \left(\frac{V_s}{344.5}\right)\sqrt{\left(\frac{298}{273 + T_1}\right)}$$

where V_s is expressed in meters per second, T_1 is gas temperature in degrees, C, P_1 is absolute pressure, and M_s is the shock-wave Mach number. When gases other than air are used, Equations 5.1 and 5.2 do not apply. (See References 2, 24, and 25 for further information.)

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5.1.1, Using Rankine-Hugoniot

- Use static-wall temperature of shock tube
- Measure velocity of shock wave using two sensors known distance apart and timing passage; pressure transducers are most common
  - 0.5% uncertainty in velocity produces at least 1% uncertainty in computed pressure-step amplitude
- Use smallest and fastest rise time transducers to minimize the rise time of the pressure step caused by passage of shock wave

5.1.1, Theoretical Rise Time

- Theoretical rise time for circular diaphragm pressure transducers mounted flush in the sidewall of a shock tube is:

(Eq. 5.4) $$t_r = \frac{0.687\,d}{V_s}$$

5.1.1, When to Use Side Mounting

- 1. When similar to application
- 2. When maximum accuracy of pressure-step amplitude is desired
- 3. To minimize transducer ringing
- 4. When incident wave is considerably cleaner than reflected wave

5.1.2, End-wall Mounting

- End of low-pressure section sealed off, shock wave will reflect from it ("reflected wave")
- Transducer flush in end plate sees only reflected wave
- Shorter rise time and higher pressure than incident wave
- Rise time (nanoseconds) short enough to excite ringing in almost all transducers

5.1.2, Pressure Step

- When air is the working gas, pressure step behind the reflected shock wave is:

(Eq. 5.5) $$\Delta P = \frac{7}{3} P_1 \left(M_s^2 - 1\right)\left(\frac{2 + 4M_s^2}{5 + M_s^2}\right)$$

where M_s and P_1 are defined as in Equations 5.1 and 5.2.

5.1.2, When to Use End-wall

- 1. To determine transducer ringing frequencies
- 2. When similar to application
- 3. When maximum pressure-step amplitude is required
- 4. When maximum duration of constant pressure behind the shock wave is desired
- 5. When transducer is recess mounted

5.1.3, Other Considerations

- Walls and end plate experience vibration
- Blank off the sensing end of the transducer from the pressure wave, without altering acceleration components
- Use heavy walled tubing and end plate
- Shock mount the tube
- Shock wave causes temperature transient, could affect some transducers

5.1.4, Recommended Operating Conditions

- When reflected mode used, should be operated under tailored conditions (Ref. 2, 26 &28)
- Transducer should be flush mounted
- Shock tube must be free of moisture and debris
- Acceleration and transient temperature characteristics should be determined before calibration

5.2, Shockless Pressure-step Generators

- Most use fast-opening valve, no shock wave
- Produce increasing or decreasing pressure steps
- Most use gas, some use liquid

5.2.3, Commercial Pressure Step Generator (1)

- Pressure step magnitude determined by measuring static pressure before & after gives good accuracy
- Duration of constant pressure after the step can be controlled
- Initial pressure and pressure step can be controlled over wide ranges
- Operation is faster and simpler than shock tube

5.2.3, Commercial Pressure Step Generator (2)

- Acceleration and temperature transients are present in shockless generator
- Not as severe as with shock tube
- Acceleration and temperature transient characteristics of transducer should be characterized before calibrating

5.2.3, Recommended Operating Conditions

- 1. Transducer flush mounted with minimum dead volume
- 2. Rise time of generator should be less than 1/5 that of the transducer
- 3. Amplitude of pressure steps should cover the range of the transducer
- 4. Calibration medium should be similar to that in use
- 5. Pressure steps should be same direction as in use

5.3, Pulse Generators

- Generate single-peaking pulses up to 100,000 psi
  - Pulses resemble half cycle of sine wave
- Drop a mass onto a piston in cylinder of incompressible fluid with fixed volume
- Amplitude depends on fluid characteristics, mass, drop height and piston area
- Requires a comparison transducer of known characteristics or acceleration reference on a known mass

5.4, Periodic Function Generators

- Ideally generate sinusoidal pressure
- Require a reference comparison transducer
- Test and reference transducers must be close together
- Reference transducer must be dynamically calibrated

5.4, Performance Requirements

- Clean sinusoidal pressure with negligible distortion
- Frequency range covers expected usage frequency range
- Operating pressure range covers expected usage pressure range
- Pressure amplitude large enough to identify possible nonlinearities in transducer response
- Calibration with same medium as usage

5.4.1, Acoustic Resonators

- Useful at low dynamic pressures
- Use acoustic resonance in a chamber
- Chamber geometry must change with frequency
- Nonlinearities and distortion become significant at higher amplitudes

5.4.2, Variable-volume Generators (1)

- Small fixed mass of working fluid, alternately compressed and expanded in small chamber
- Chamber has high natural frequency to avoid resonant effects
- Piston or diaphragm varies pressure
- “Pistonphone” is an example
- Mostly used for sound pressure calibrators

5.4.2, Variable-volume generators (2)

- Isentropic compression; pressure follows piston position
- Po = equilbrium pressure
- ℓo = equilibrium piston position
- γ = ratio of specific heats

(Eq. 5.6)

$$\frac{p}{p_o} = \left(\frac{\ell_o}{\ell}\right)^{\gamma}$$

5.4.2, Variable-volume generators (3)

- If piston motion is sinusoidal, pressure can be expressed by Eq. 5.7; and dynamic pressure by Eq. 5.8 (clearly nonsinusoidal)
- Limited amplitude and frequency ranges

(Eq. 5.7) $$p = p_o (1 + \alpha \sin \omega t)^{-\gamma}$$

and the dynamic pressure amplitude by the expression

(Eq. 5.8) $$\Delta p = p_o - p = p_o [1 - (1 + \alpha \sin \omega t)^{-\gamma}] = \alpha \gamma p_o \sin \omega t - \frac{\alpha^2}{2} p_o \gamma (\gamma + 1) \sin^2 \omega t \ldots$$

where α = modulation factor, which is always < 1.

5.4.3, Variable-mass Generators

- Fixed chamber volume with rate of fluid flow into or out of the chamber varied to produce dynamic pressure pulsations
- Larger pressure amplitudes at high frequencies than the variable-volume generators
- Siren-type devices modulating flow from a constant pressure source
- Not commercially produced for pressure calibration

5.4.4, Fluidic Pressure Generator

- Potential for dynamic pressure calibrations, but not well-developed
- Produce low-amplitude pressures, but capable of wide dynamic range
- High frequency capability
  - up to over 100 kHz
- Not commercially developed for dynamic pressure calibration

5.4.5, Recommended Operating Conditions (1)

- 1. Maximum (peak) pressures within linear range of reference transducer
- 2. Maximum frequency less than 1/5 natural frequency of reference
- 3. Clean sinusoidal wave form per reference transducer
- 4. Minimum of 10 discrete frequencies or continuous (swept) frequencies

5.4.5, Recommended Operating Conditions (2)

- 5. Reference and test transducers located within 1/10 wavelength of highest frequency
- 6. Record reference and test transducer outputs simultaneously
- 7. Indicated average and dynamic pressures determined for each test point with reference transducer

5.4.5, Recommended Operating Conditions (3)

- 8. Minimize fatigue and thermal effects by short-time operation at each test point
- 9. Integral cooling systems in test transducer should be activated during calibrations
- 10. Media should be same as in use
- 11. Reference transducer should be dynamically calibrated

6, MEASUREMENT OF TRANSDUCER PROPERTIES

- Pressure transducer calibration could more accurately be called "characterization"
- Complete calibration involves determining several characteristics or properties of a transducer

6.1, Sensitivity (1)

- May be established with periodic or aperiodic pressure generators
- Preferable to use a method that does not require a reference transducer
- Shock tubes can provide uncertainties approaching 2%
- Other techniques may be even better, but may be limited in amplitude or frequency range

6.1, Sensitivity (2)

- Step pressure sources produce oscillatory output
- In shock tube reflected wave may disturb transducer before oscillations decay
- Quick-opening valve generators apply undisturbed pressure long after oscillations decay

6.1, Sensitivity (3)

- If transducer does not respond to static pressure, waiting for oscillations to decay may contribute error
- Example: RC roll-off at 1 Hz will decay 5% in approximately 8 milliseconds
- Sinusoidal generators are more straightforward, but limited in amplitude and frequency

6.2, Amplitude Response (1)

- Most important and most difficult to obtain
- Ideally calibrated with swept sinusoidal generator
- Sine generators not flat frequency response
- Need reference transducer for comparison
- Natural frequency of reference must be at least 5 times measurand frequencies

6.2, Amplitude Response (2)

- Sinusoidal generators incapable of high enough frequencies
- Some dynamic pressure transducers have frequency response to 500 kHz or greater
- Require aperiodic generator like shock tube

6.2.1, Sinusoidal Pressure

- Acoustic effects limit practicability of sinusoidal generators at high frequencies
- Practical frequency limit is a few thousand hertz
- Higher frequencies produce distortions
  - May affect response of test or reference
  - May affect test and reference differently
- RMS detection is recommended for all steady-state sinusoidal measurements

6.2.2, Aperiodic Sources

- Shock tube can provide amplitude and phase response by transforming output from time domain to frequency domain
- Assume pressure input is step function
- Best to use reflected wave (end-wall mounting) to get closest to step function
- Acceleration, thermal, and coupling port effects must be minimized
- Recommended sampling rate 5 times highest frequency

6.3, Phase Response

- Reference transducer should have negligible phase shift in test frequency range
- Located test and reference transducers on opposite sides of measurement cavity
- Electronic filter cutoff frequency at least a decade above measurement frequencies
- Derive from shock tube measurement (FFT)

6.4, Resonant Frequency

- Best determined by reflected wave in shock tube
- Determine from peak of frequency response curve
- Calculate from ringing frequency:

(Eq. 6.2) $$\omega_r = \sqrt{\frac{1-2\zeta^2}{1-\zeta^2}}\,\omega_d$$

6.5, Ringing Frequency

- Response of an underdamped transducer to a step or impulse input; damped oscillatory transient
- Frequency can be derived from time history
- May have multiple ringing frequencies
- Frequency response below lowest ringing frequency approximates SDoF

6.6, Damping Ratio (1)

- Can be obtained from amplitude response using sine-wave generator
- Can be measured using an aperiodic generator

6.6, Damping Ratio (2)

- Amplification factor of resonance on amplitude-ratio curve is related to damping ratio, and is plotted in Fig. 1:

(Eq. 6.3) $$A_r = \frac{1}{2\zeta\sqrt{1-\zeta^2}}\ ;\ 0 \le \zeta \le 0.707 = 1;\ 0.707 \le \zeta \le 1$$

6.6, Damping Ratio (3)

- Solving that relationship for ζ:

(Eq. 6.4) $$\zeta^2 = \frac{1-\sqrt{1-1/A_r^2}}{2}$$

6.6, Damping Ratio (4)

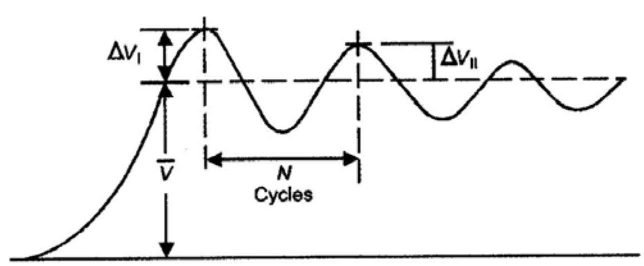
- With step input, damping ration can be calculated from Eq. 6.5, where N is the number of complete cycles over which the measurement is made

(Eq. 6.5)

$$\zeta = \left[1 + \left\{ \frac{2\pi N}{2.303 \log_{10}\left(\frac{\Delta V_1}{\Delta V_2} \right)} \right\}^2 \right]^{-1/2}$$

6.6, Damping Ratio (5)

- Oscillatory response for Eq. 6.5



6.6, Damping Ratio (6)

- Best accuracy is achieved when N = 1
- Then, Eq. 6.5 becomes:

(Eq. 6.6)

$$\zeta = \left[1 + \left\{ \frac{2.728}{\log_{10}\left(\frac{\Delta V_1}{\Delta V_2}\right)} \right\}^2 \right]^{-1/2}$$

6.7, Rise Time

- Apply step input and measure time for output to go from 10% to 90% of final value
- Rise time of step input must be less than 1/5 rise time of transducer for <1% error
- Rise time of recording system must be short enough to introduce negligible error

6.8, Overshoot

- Observe response to step input
- Overshoot is peak output – average output divided by average output:

(Eq. 6.7) $$\text{Overshoot} = \left(\frac{V_p - \overline{V}}{\overline{V}}\right) 100 \text{ in percent}$$

7, TRANSDUCER INTERFACES

- When installing for calibration or measurement consider:
- 1. Strain effects
- 2. Cavity of passage resonances
- 3. Temperature effects
- 4. Acceleration effects
- Other environmental and physical factors may affect accuracy or noise

7.1, Mounting, Strain Effects

- Non-precision mounting or over-torquing may cause strain in the transducer housing
- May show up as change of sensitivity, zero shift or mechanically induced noise
- Can be evaluated by calibrating with recommended torque, then with over-torque and/or under-torque

7.2, Cavities & Passages

- Any connecting line or cavity between the test transducer and the pressure source will affect transducer response
- Effect gets worse as frequency increases
- Above 10 kHz transducer must be flush mounted
- Mount in same configuration as intended use

7.3, Temperature Effects (1)

- Many pressure transducers experience a change of sensitivity or a change of zero output caused by temperature difference
- May also be affected by transient temperature
- Temperature effects must be evaluated and characterized before attempting to calibrate

7.3, Temperature Effects (2)

- Evaluate with steady state or sinusoidal pressure at two or more stabilized temperatures
- Evaluate with steady state or sinusoidal pressure while rapidly changing or cycling temperature
- Evaluate with steady state or sinusoidal pressure while exposing sensing surfact to heat lamp and/or electronic flash

7.3.1, Liquid-cooled Transducers

- One method of reducing temperature effects is to provide liquid cooling
- Intrinsic cooling uses passageways in the transducer case and/or diaphragm
- Cooled adapter provides a liquid cooled mounting adapter
- Cooling should be activated during temperature characterization and calibration

7.3.2 Gas-bleed Method

- In the most extreme temperature environments (i.e. rocket engines), constant flow of cool gas (helium) is bled into a cavity in front of the diaphragm from a high pressure supply
- Provides heat shield and minimizes passage resonances
- Shock tube calibration can help determine best gas bleed parameters

7.3.3, Diaphragm Coatings

- Silicone rubber or silicone grease may be applied to the transducer diaphragm to protect from short-term exposures
- Properly applied, has little effect on performance above about 10 psi full scale ranges
- Most accurate calibration requires that the coating be in place

7.4, Acceleration Effects

- Dynamic pressure may cause vibrations in the mounting structure; may induce acceleration and/or strain effects in transducer
- Evaluate by mounting transducer in a blind hole (to block pressure) and perform calibration process
- Any output must be caused by non-pressure effects

8, ELECTRONIC CONSIDERATIONS

- Signal conditioning and data acquisition and recording equipment must be compatible with test and standard units
- Rise time less than 1/5 that of transducer
- Frequency response should introduce negligible error over calibration frequency range

8.1, Noise

- Noise may be a problem if transducer output is low
- Noise may originate in any part of the system
- Insufficient signal to noise ratio makes calibration data difficult to interpret

8.1.1, Transducer Noise

- Acceleration, thermal effects, electromagnetic fields, improper mounting may cause noise
- Noise may be generated internally by strain gage elements or electronic circuitry
- Low-impedance output transducers are generally less susceptible to these sources than high-impedance

8.1.2, Cable Noise

- Cable may pick up extraneous noise or may generate noise internally
- Friction between layers of cable may generate static charges (PE transducers are especially susceptible)
- Imperfect shielding or ground loops may induce noise
- IEPE transducers are less susceptible

8.1.3, Amplifier Noise

- All amplifiers have a noise characteristics
- Usually quantified referred to the input
- Independent of input cabling

8.1.4, System Noise

- All previously mentioned sources plus inductively and capacitively coupled noise
- Proper grounding, avoiding ground loops, and differential amplifiers minimize
- Shielded twisted pair or coaxial cabling plus single point ground minimize
- Use dependable, verifiable ground point

8.2, Cabling

- PE transducers require high quality low-noise coaxial cable
- IEPE and bridge-type transducers minimize cable noise problems
- Ideal calibration uses same cable as in intended use

8.3, Voltage Amplifier

- Bridge type and IEPE transducers use voltage amplifiers for impedance matching and for ranging signal for downstream
- PE transducers should not be used with an older voltage type amplifier – use a charge amplifier instead

8.3.1, Slew Rate

- Maximum rate of change of output voltage from the amplifier (especially for large signals)
- Slew rate limits maximum frequency and minimum rise time for full-power response from amplifier

$$\frac{de}{dt} = 2\pi f^{E} \quad \text{(Eq. 8.2)}$$

9, DATA ACQUISITION & ANALYSIS

- Data acquired by digital oscilloscope or recorder
- Analyze in time domain
- Analyze in frequency domain

9.1, Digital Oscilloscope or Recorder

- With shock tube, rise-time should be less than 1/5 that of the signal
- Can be measured by application of a square wave to properly terminated input terminal
- Frequency response determined by sampling rate and anti-alias filtering
- Best if flat to frequency beyond resonance of transducer

9.2, Data Analysis

- May be time domain analysis for amplitude calibration, damping determination, etc.
- May be frequency domain analysis for transfer function, etc.

9.2.1, Time Analysis

- Only requires faithful reproduction of waveform of test and reference transducers
- Flat amplitude and linear phase response are required over full frequency range
- Sampling rate should be high enough, and anti alias filter selected, to avoid aliasing

9.2.2, Frequency Analysis

- Multi-channel spectrum analyzers available
- FFT of each channel or transfer function between reference and test channels
- Coherence function should be near 1.0 over the frequency range

10, REPORTING TEST RESULTS

- Data presented in meaningful manner
- Information depends on complexity of equipment and procedures
- May require detailed explanation of test conditions and supporting information

10.1, Test Conditions

- Test equipment
- Environmental conditions
- Mounting configuration
- Special considerations

10.1.1, Test Equipment

- Unique or non-standard equipment requires description and definition of capabilities
- Use recorded-time histories of reference transducer and response of readout equipment to square wave inputs
- Transfer function and coherence may be useful

10.1.2, Environmental and Related

- Dynamic pressure changes are often accompanied by rapid temperature changes, vibration and acceleration
- Comments or data explaining their effects
- Output of blocked-off transducer in shock tube test, for example

10.2, Results and Discussion

- Transducer response to pressure step in shock tube
- Other previously mentioned data
- Definition of terms used

References

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- 2. Jim Lally and Dan Cummiskey, “Dynamic Pressure Calibration”, Sensors Magazine, Vol. 20 No. 4, April 2003
- 3. ISA-S37.16.01-2002, “A Guide for the Dynamic Calibration of Pressure Transducers, Instrument Society of America

More References

- 4. Jon S. Wilson (Ed.), Dynamic Pressure Measurement Technology, Publ. Endevco, San Juan Capistrano, CA, 1991
- 5. Abundant references (77) provided in the standard.

CONCLUSION

QUESTIONS, COMMENTS & DISCUSSION

THANK YOU FOR YOUR PARTICIPATION

CONTACT INFORMATION:

- Jon Wilson, Principal Consultant
  The Dynamic Consultant, LLC
  4959 East Karsten Drive
  Chandler, AZ 85249-7175
  Voice & FAX: 480-699-9274
  Email: Dynamic-Consultant@Cox.net