



OPERATING MANUAL
for
QUARTZDYNE®
Frequency Output Pressure Transducers

QUARTZDYNE, INC.
A DOVER COMPANY

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Quartzdyne Frequency Output Pressure Transducer Operating Manual

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1 GENERAL INFORMATION

1.1 Introduction

This Manual documents the electrical interface for QUARTZDYNE® Frequency Output Pressure Transducers.

All QUARTZDYNE® Pressure Transducers contain three quartz crystal sensor elements. The first of these is sensitive primarily to exposed pressure, the second responds to temperature, and the third has minimal sensitivity to either pressure or temperature. The crystals are arranged mechanically to provide good thermal coupling. The quartz sensing elements provide high stability and extremely fine resolution for sensing pressure. A bellows is used to protect the pressure crystal from the process fluids. A circuit provides stimulus for the quartz sensing elements, and the corrosion-resistant, high-strength alloy housing provides mechanical support and protection to each of these elements. Various mechanical configurations are available.

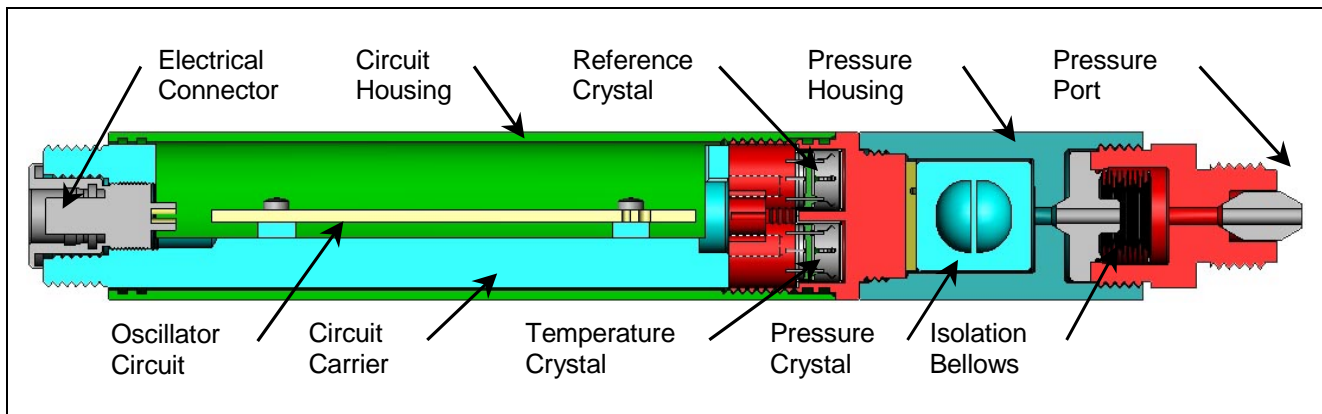


Figure 1. Parts of a QUARTZDYNE® Pressure Transducer (Model QUB shown).

The circuit consists of three oscillators, two mixers, buffering circuitry and a regulator. The outputs are two low frequency (10-100kHz) sensor output signals and a high frequency (7.2 MHz) reference signal. The transducer must be connected to a frequency counter and power supply. The high frequency reference signal may be used to count the two low frequency signals using the "reference-based" coefficients. Alternatively, the user may supply another reference signal and use the "standard" coefficients. Pressure is computed using the two low frequency signals, the unique calibration coefficients for the transducer, and the algorithm shown in this manual. Temperature may also be calculated from the frequencies.

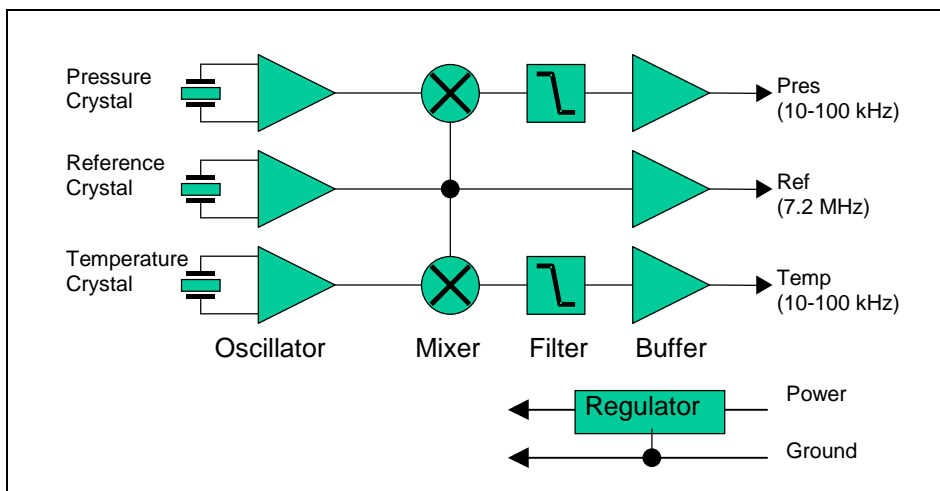


Figure 2 . Oscillator Circuit Block Diagram.

2 THEORY OF OPERATION

2.1 Pressure Sensor Design

The important advantages of the QUARTZDYNE® thickness-shear pressure technology are precision, long-term stability, ruggedness, and rapid transient response.

The pressure sensor is a quartz resonator that changes frequency in response to applied pressure. Crystalline quartz is an ideal material for precision sensors because it is perfectly elastic. The design of the QUARTZDYNE® quartz pressure sensor retains the repeatable performance inherent in the single-crystal material.

The quartz pressure sensor is a thick-walled, hollow cylinder with closed ends. A thickness-shear mode resonator divides the central portion of the hollow cylinder. Fluid pressure on the exterior walls hydrostatically compresses the quartz cylinder, producing internal compressive stress in the resonator. The frequency of the resonator changes in response to the internal stress.

2.2 Pressure Measurement System Design Theory

The *transducer* is the assembly required to convert the physical parameters of pressure and temperature into the frequency output signals. Each transducer assembly includes the quartz pressure sensor, a temperature sensor crystal (for digital temperature compensation), and a precision reference crystal. An oscillator circuit provides stimulus to the quartz elements, converting their natural resonant frequencies into electrical signals. The reference crystal's frequency is mixed with the frequencies from the two sensors to make these signals easier to count and transmit. It also provides the transducer with a stable time base that can be used in the user's frequency counter.

For a complete measurement system, the user must provide power, a frequency counter, means for calculating pressure from the measured frequencies and provided coefficients, and either storage or a transmission method for the data. Digital transducers are available from Quartzdyne, which include the frequency counter and coefficient storage. Interface units are also available which calculate pressure and temperature and provide basic data logging functions (Figure 3).

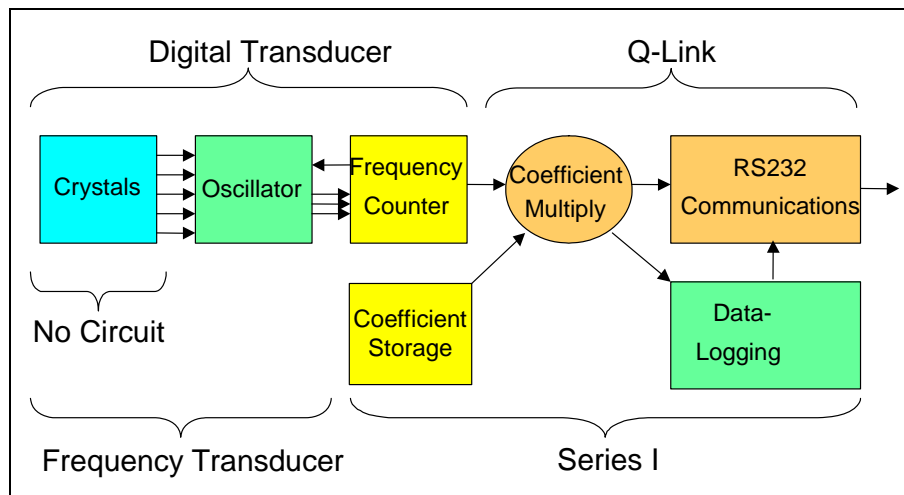


Figure 3. Function blocks for QUARTZDYNE® quartz pressure measurement systems. Each bracketed block is available from Quartzdyne.

2.3 Frequency Changes with Pressure and Temperature.

Nominal frequency sensitivities to pressure and temperature for the various sensors are shown on the data sheets of the respective products. Figure 4 through Figure 7 depict the typical change in the frequencies of the two output signals of a QU20K transducer with changes in pressure and temperature. Figure 4 shows the nominal change in frequency of the temperature sensor. All temperature sensors show very similar sensitivities, but the frequency at

25°C will vary from unit to unit. Figure 5 shows the change in frequency of the pressure signal with changes in pressure and temperature. Note that changes in temperature produce changes in both zero and span.

The data from Figure 5 has been re-plotted in Figure 6 for additional examination. In Figure 6, the pressure frequency data is plotted versus temperature at various pressures. The data has also been normalized at the minimum frequency so that the temperature sensitivity can be observed more clearly. Note that the temperature sensitivity is positive at ambient pressure, but negative at full-scale pressure, with a zero sensitivity point that occurs at higher temperatures as the pressure is increased.

The pressure sensor has been designed to minimize transient errors in downhole work. Care has been taken to provide good thermal coupling between the pressure and temperature crystals. Under transient conditions (temperature ramps, or large pressure steps), a small temperature difference is possible. Figure 7 shows the nominal sensitivity of the pressure sensor due to temperature differences that may occur during a transient condition. If the transducer is used in the typical down-hole pressure and temperature ranges where the sensitivity is in the zero to 10psi/°C range, the transient errors will be small. Conversely, if used at the extremes of high temperature - low pressure, or high pressure - low temperature, the transient errors will be more significant. See our website for a detailed transient report comparing the performance of various pressure transducer configurations.

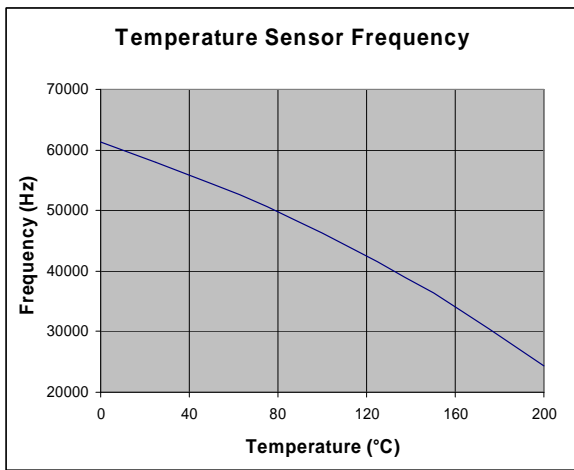


Figure 4. Typical Temperature Sensor frequency as a function of temperature.

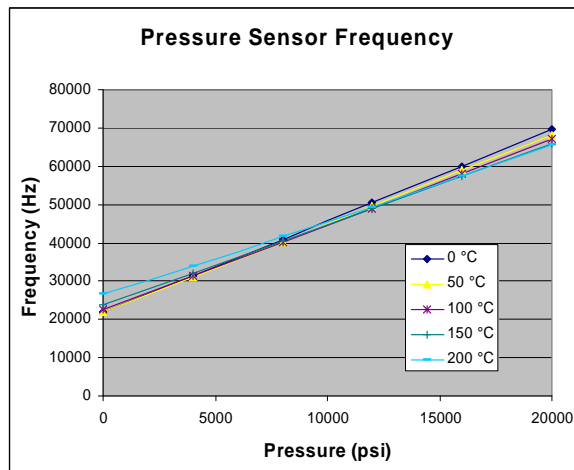


Figure 5. Typical Pressure Sensor frequency at various temperatures.

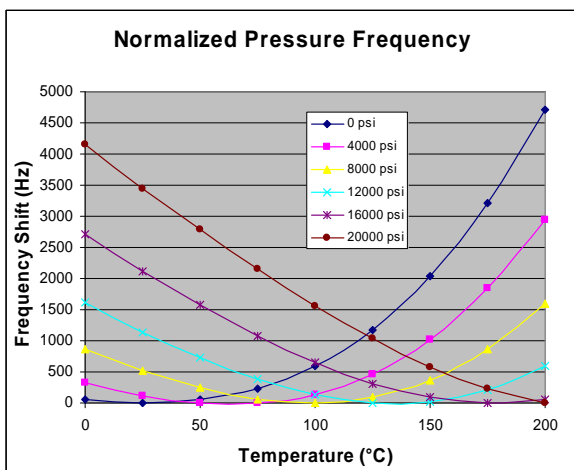


Figure 6. Pressure Sensor frequency plotted vs. temperature and normalized to the minimum (zero - sensitivity) point for each pressure.

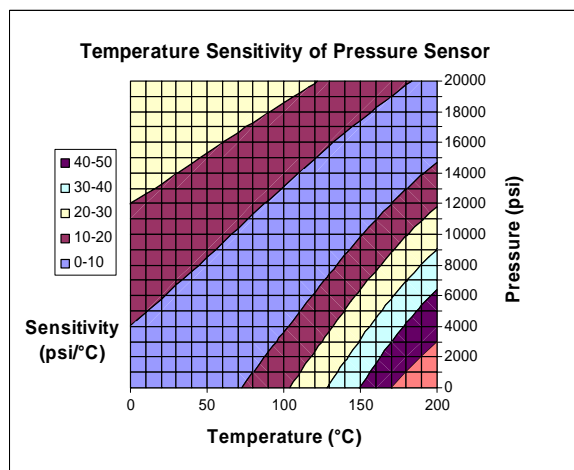


Figure 7. Pressure Sensor Temperature sensitivity gradient plot showing low sensitivity along a typical well gradient. Transient errors will be worse in ranges with high sensitivity.

3 Operation

3.1 Electrical Connection to QUARTZDYNE® Transducers

Several electrical connection options are available for QUARTZDYNE® Frequency Output Transducers. See Figure 8 for pin-out assignments. In applications requiring high reliability, solder connections are preferred to connectors. The 5-Pin 1" feed through, the 6-Pin PEEK Header and the 7-Pin Hermetic Header are designed for direct soldering using high melting point solders. In some cases, an installed connector can be removed exposing 2-4" of wires, which can be soldered directly to the user's circuit. Table 1 shows standard wire colors for units where flying leads are provided. Table 1 shows standard wire colors for units where flying leads are provided.

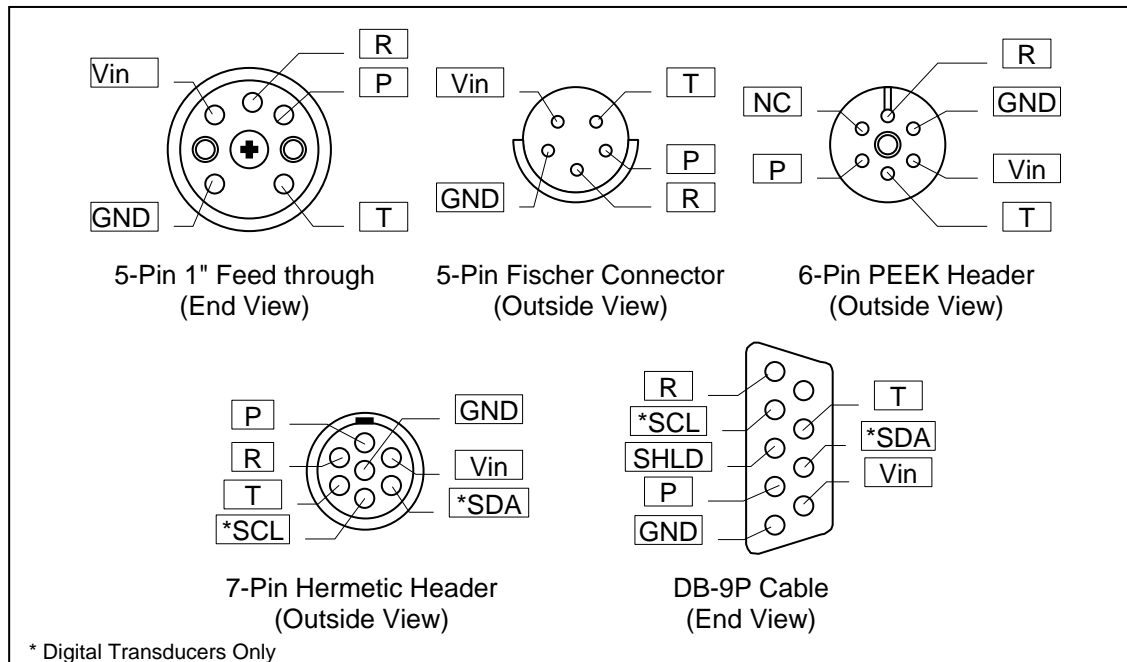


Figure 8. Pin assignments for various QUARTZDYNE® Transducer connector options

Table 1. Pin and wire labels and their functions

Label	Function	Wire Color (Std)	Alternate Colors
Vin	Power Supply (Pos)	Blue (3-5V)	Red (5-12V)
GND	Power Supply (Neg)/Chassis	Black	Black
SHLD	Shield Termination/Chassis		
R	Reference Frequency Output	White	White
P	Pressure Frequency Output	Purple	Purple
T	Temperature Frequency Output	Yellow	Yellow
*SCL	SCL for Digital Transducers Only	Slate	N/A
*SDA	SDA for Digital Transducers Only	Green	N/A

WARNING! The oscillator circuit can be damaged if excess current or voltage is applied to the pins. Always use current-limited power supplies to prevent excessive current when the device is incorrectly wired.

WARNING! The GND pin is internally connected to chassis. High currents will flow if a grounded power supply is incorrectly connected to this pin. Currents of several Amps are possible while power supply filter capacitors are being discharged.

WARNING! Avoid static discharge when handling transducers, and particularly when mating connectors. Fully discharge the cable to the chassis of the transducer before mating the connector. Store and transport transducers in static-safe containers.

3.2 Computing Pressure from Frequencies and Coefficient Files

WARNING! Do not assume that the fit order, pre-scaling factors, or SPAN and ZERO numbers are constant. These are subject to change from sensor to sensor. Quartzdyne reserves the right to change these at any time without notice. Always design systems that support these fields as variable.

The transducer is supplied with an ASCII text coefficient file. The file name is the serial number of the transducer followed by one of four file extensions indicating the type of coefficients. If the transducer's internal 7.2 MHz reference frequency is used as the time base in frequency counting, use the coefficient files with the extension .CRF and .CRT. If some other time base frequency is used in counting, use the files with the extension .CFF and .CFT.

123456.CFF	Standard Pressure Coefficients
123456.CFT	Standard Temperature Coefficients
123456.CRF	Reference-Based Pressure Coefficients
123456.CRT	Reference-Based Temperature Coefficients

The internal format of each file type is the same. Each line in the file represents a single field as described below. No blank lines or comments are allowed.

Table 2. Coefficient File Format

Line	Symbol	Description	Typical Value (.CRF)	Typical Value (.CRT)
1	S/N	Pressure Sensor ID	157879R	157879R
2	CT	Calibration Type	Pressure	Temperature
3	CU	Calibration Units	psia	°C
4	NT	Polynomial Order in Temperature*	3	3
5	PT	Temperature Prescale Algorithm	1	1
6	MT	Temperature Scaling Factor*	0.01	0.01
7	FT0	Temperature Offset Frequency*	58020	58020
8	NP	Polynomial Order in Pressure*	3	0
9	PP	Pressure Prescale Algorithm	1	1
10	MP	Pressure Scaling Factor	0.01	0.01
11	FP0	Pressure Offset Frequency	21982	21982
12	A0	First Fit Coefficient	1.10390186144E+01	2.51641904936E+01
13	A1	Fit Coefficient	-1.28452244351E-01	-7.27120283063E-01
.	.		.	.
.	.	Number of coefficients is variable (≤ 25);	.	.
.	.	$N = (NT+1) * (NP+1)$.	.	.
.	.		.	.
N+11	D3/A3	Last Fit Coefficient (Symbol varies with NT, NP)	-2.91212554073E-14	-6.78716126821E-07
N+12	SPAN	May be used for units conversion	1.000000000000	1.000000000000
N+13	ZERO	May be used for units conversion	0	0
N+14	TMIN	Minimum temperature of calibration (°C)	25	25
N+15	TMAX	Maximum temperature of calibration (°C)	175	175
N+16	PMIN	Minimum pressure of calibration (psia)	12	12
N+17	PMAX	Maximum pressure of calibration (psia)	20000	20000
N+18	DATE	Date of calibration	08 Sep 2003	08 Sep 2003
N+19	Model	Transducer model	SPB002-20-177	SPB002-20-177

* **Warning!** Typical values are not fixed, and should not be assumed. These are subject to change without notice.

The first three lines and the last six lines help to identify the transducer and its pressure and temperature range of calibration. The Pressure Sensor ID uniquely identifies the transducer. ("R" in the Pressure Sensor ID indicates reference-based coefficients. See Section 4.5). The instrument type and units are provided in the coefficient file to allow for calibrations in different units and of different parameters. All pressure transducers calibrated by Quartzdyne, Inc. are calibrated to PRESSURE in psi absolute and Temperature in °C. Units conversion can be accomplished by

using the appropriate "SPAN" and "ZERO" values. Be sure to edit Line 3 ("Calibration Units") appropriately. The equation allows the zero to be entered in the desired units:

$$\text{Output(Desired Units)} = \text{SPAN} * \text{Output(base units)} + \text{ZERO(Desired Units)}.$$

$$\text{Pressure(bar)} = 0.0689476 * \text{Pressure (psia)} + 0$$

$$\text{Temperature (}^{\circ}\text{F)} = 1.8 * \text{Temperature (}^{\circ}\text{C)} + 32 \text{ }^{\circ}\text{F}$$

For Pressure, the typical polynomial fit order is NP = 3 and NT = 3 or 4. The values of NP and NT will vary depending on sensor technology, and the temperature and pressure ranges of the calibration. For Temperature, NP is typically 0, while NT is usually 3. The user is cautioned not to hard-code this fit order or assume that NP will always be zero. Historic and future transducer designs may include temperature frequency outputs with some pressure sensitivity. Both the temperature frequency and the pressure frequency should be used to calculate temperature. In Quartzdyne calibrations, the product of (NT + 1)* (NP + 1) will not exceed 25 for either coefficient type. The output can be calculated from the two frequencies as follows:

Scale the frequencies according to the prescale algorithm specified in the coefficient file. All QUARTZDYNE® Pressure Transducers use Prescale Algorithm type 1 (PT = PP = 1) which has the following form:

$$\begin{array}{ll} \text{PRESSURE PRESCALE:} & \text{XP} = \text{MP}(\text{FP} - \text{FP0}) \\ \text{TEMPERATURE PRESCALE:} & \text{XT} = \text{MT}(\text{FT} - \text{FT0}), \end{array}$$

where FP and FT are the measured pressure and temperature frequencies, respectively.

The output is calculated from the coefficients and the two pre-scaled values, XP and XT, using the following equation:

$$\text{Output} = \text{A} + \text{XP}(\text{B} + \text{XP}(\text{C} + \text{XP}(\text{D} + \text{XP}(\text{E}))))),$$

where the coefficients A, B, C, D, and E are computed as:

$$\begin{array}{l} \text{A} = \text{A0} + \text{XT}(\text{A1} + \text{XT}(\text{A2} + \text{XT}(\text{A3} + \text{XT}(\text{A4})))) \\ \text{B} = \text{B0} + \text{XT}(\text{B1} + \text{XT}(\text{B2} + \text{XT}(\text{B3} + \text{XT}(\text{B4})))) \\ \text{C} = \text{C0} + \text{XT}(\text{C1} + \text{XT}(\text{C2} + \text{XT}(\text{C3} + \text{XT}(\text{C4})))) \\ \text{D} = \text{D0} + \text{XT}(\text{D1} + \text{XT}(\text{D2} + \text{XT}(\text{D3} + \text{XT}(\text{D4})))) \\ \text{E} = \text{E0} + \text{XT}(\text{E1} + \text{XT}(\text{E2} + \text{XT}(\text{E3} + \text{XT}(\text{E4})))) \end{array}$$

The expansion above is for the maximum number of coefficients (a value of 4 is used for both NP and NT). For a typical case of NP = 3 and NT = 3, the terms A4, B4, C4, D4, and E0 through E4 will not be included. See the utility software available on our website for example programs for reading coefficients and computing pressure and temperature. The example code in the following section can be used for the calculation.

3.3 Example Calculation Function (BASIC)

```

'Inputs:
'Double Fp, Ft           -- Frequency As Measured
'Double Mp, Fp0, Mt, Ft0 -- Prescaling Factors from coefficient file
'Integer Np, Nt         -- Fit order from coefficient file
'Double C( (N1+1) * (N2+1) ) -- Coefficients from Coefficient file
'Double SPAN, ZERO      -- Units Conversion from Coefficient file
'
'Output:
'Double qdCfCalc
'
'Variables:
'Double Xp, Xt          -- Scaled frequencies
'Double Z1, Z2         -- Accumulators for factored polynomial calculation
'Integer I, J, N       -- Loop counters
'
Function qdCfCalc (Fp As Double, Ft As Double, _
    Mp As Double, Fp0 As Double, Mt As Double, Ft0 As Double, _
    Np As Integer, Nt As Integer, _
    C() As Double, SPAN As Double, ZERO As Double) As Double

Dim Xp, Xt, Z1, Z2 As Double
Dim I, J, N As Integer

Xp = Mp * ( Fp - Fp0 )      ' prescale pressure frequency
Xt = Mp * ( Ft - Ft0 )      ' prescale temperature frequency
N = (Np+1) * (Nt+1)        ' index of last coefficient

Z1 = 0                     ' accumulator for outer loop
For I = 0 to Np             ' outer loop for Np, Xp
    Z1 = Z1 * Xp            ' compute polynomial in Xp (Result is zero on first pass)

    Z2 = 0                 ' accumulator for inner loop
    For J = 0 to Nt         ' inner loop for Nt, Xt
        Z2 = Z2 * Xt        ' compute polynomial in factored form for maximum efficiency
        Z2 = Z2 + C(N)      ' Z2 = c(0)+Xt*( C(1)+Xt*( C(2) + . . . + Xt*( C(N) ) ) )
        N = N - 1          ' work through coefficients from last to first
    Next J

    Z1 = Z1 + Z2            ' add inner-loop total as a coefficient to outer loop total
Next I

Z1 = SPAN * Z1 + ZERO      ' Apply units conversion
qdCfCalc = Z1              ' Return result

End Function

```

4 Frequency Counting

The pressure resolution that is available from a Downhole Transducer is a function of the user's time base frequency, the gate time during which the frequency is counted, the pressure sensitivity of the pressure sensor, and the method of frequency counting. The two most common methods of counting are direct frequency counting and period (or reciprocal) counting. Both of these will be discussed below. The following definitions will be used:

T_G	=	gate time (sec)
F_R	=	reference crystal or time base frequency (Hz or MHz)
F_S	=	sensor frequency (Hz or MHz)
N_R	=	number of counts of reference during T_G
N_S	=	number of counts of sensor during T_G
S_{PP}	=	Pressure Sensor Pressure Sensitivity (Hz/psi)
S_{PT}	=	Pressure Sensor Temperature Sensitivity (Hz/°C)
S_{TP}	=	Temperature Sensor Pressure Sensitivity (Hz/psi)
S_{TT}	=	Temperature Sensor Temperature Sensitivity (Hz/°C)
R	=	Resolution (psi or Hz)

Some of the equations shown below refer to the nominal sensitivities and frequency ranges of the pressure and temperature sensors. Please refer to the various product specification sheets for actual sensitivities.

4.1 Direct Frequency Counting

Direct frequency counting is simple and can be used with any time base. Its disadvantage is that it has poor resolution with low sensor frequencies. It is only preferred if the sensor frequency is higher than the user's time base frequency. It is generally not appropriate for QUARTZDYNE® transducers, but is included in this discussion for comparison purposes.

Direct Frequency Counters use the time base frequency to determine the gate time during which the sensor frequency is counted (Figure 11). Usually, the implementation provides for the gate time, t , to be determined by a fixed number of counts of the reference, or time base frequency:

$$T_G(\text{sec}) = \frac{N_R(\text{counts})}{F_R(\text{Hz})}$$

The sensor frequency is calculated from the number of counts of the sensor signal during the gate time:

$$F_S(\text{Hz}) = \frac{N_S(\text{counts})}{t(\text{sec})}$$

In direct frequency counting, the frequency resolution is a function of the gate time. For example, a one second gate time provides 1 Hz resolution; longer gate times provide higher resolution:

$$\text{Frequency Resolution (Hz)} = \frac{1}{T_G(\text{sec})}$$

The pressure or temperature resolution in direct frequency counting is a function of the gate time and the sensitivity of the sensor:

$$R(\text{psi}) = \frac{1}{T_G(\text{sec})} \frac{1}{S_{PP}(\text{Hz/psi})}$$

$$R(^{\circ}\text{C}) = \frac{1}{T_G(\text{sec})} \frac{1}{S_{TT}(\text{Hz/}^{\circ}\text{C})}$$

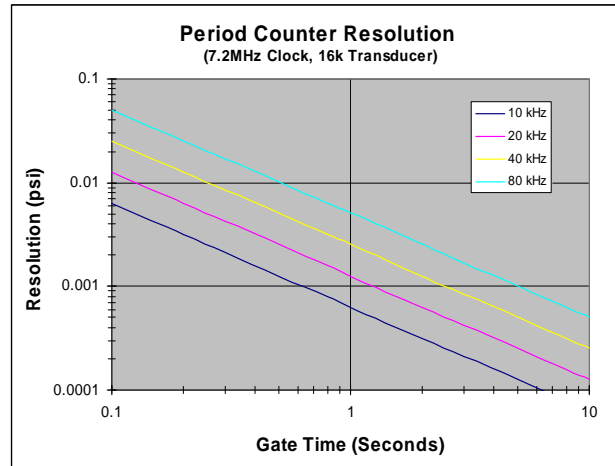
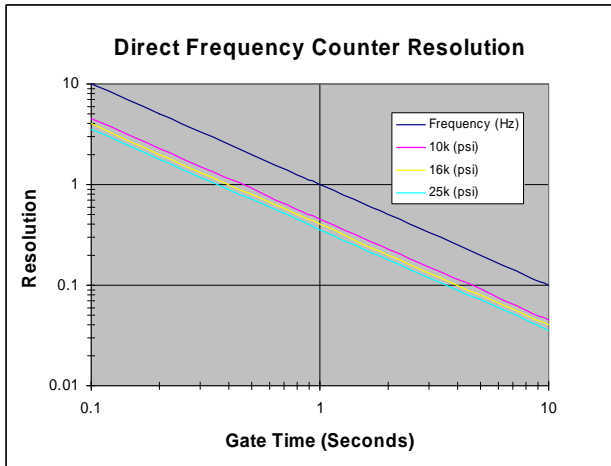


Figure 9. Resolution provided by a direct frequency counter as a function of gate time in Hz, and in psi for various sensor types.

Figure 10. Resolution of a Period Counter for a typical 16k transducer. Note that for a Period Counter, resolution is a function of gate time and sensor frequency.

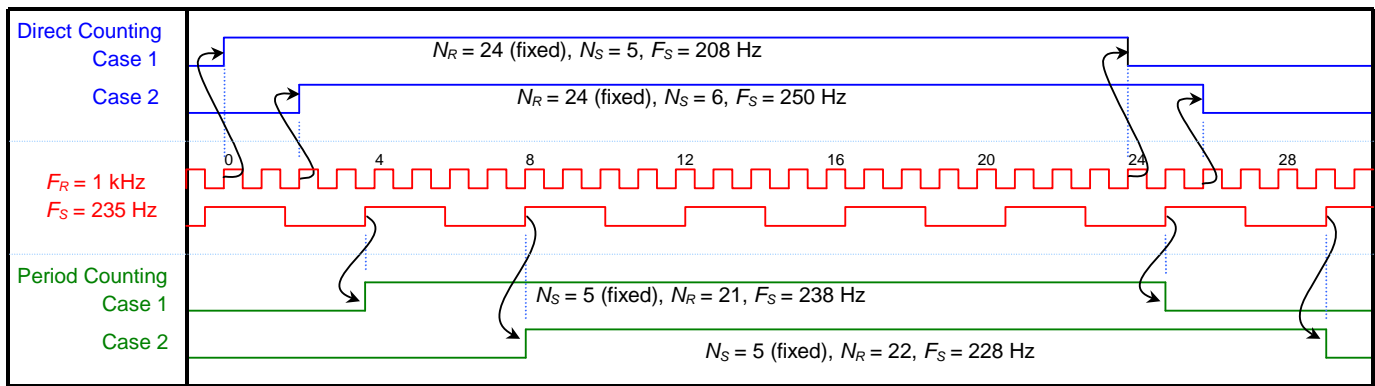


Figure 11. With Direct Frequency Counting the gate opens for a fixed number of counts of the Reference Frequency while Sensor Frequency Counts are accumulated. With Period Counting the gate opens for a fixed number of counts of the Sensor Frequency while Reference Counts are accumulated. Resolution is improved when the variable counts are higher. In this example, the Direct Counter has 42 Hz resolution while the period counter is able to resolve 10 Hz.

4.2 Period Counting

Period counting, also called reciprocal counting, uses the sensor frequency to determine the gate time during which the reference frequency is counted. This method can provide much higher resolution than direct frequency counting using a high frequency time base. The sensor frequency is calculated from the reference frequency and the number of counts of the sensor and reference frequencies during the gate time:

$$F_S (Hz) = \frac{F_R (Hz) N_S}{N_R}$$

In period counting, the frequency resolution is a function of the frequency being measured and the total number of counts of the time base frequency:

$$R (Hz) = \frac{F_S (Hz)}{N_r} = \frac{F_S (Hz)}{F_R (Hz) T_G (sec)}$$

To determine the resolution both the frequency and sensitivity of the sensor must be known:

$$R(psi) = \frac{F_s(Hz)}{F_R(Hz)t(sec)S_{PP}(Hz/psi)}$$

$$R(^{\circ}C) = \frac{F_s(Hz)}{F_R(Hz)t(sec)S_{TT}(Hz/psi)}$$

Figure 10 shows the gate time required for the desired pressure resolution of a typical 16k Downhole Transducer. Note that the resolution is a function of the sensor frequency, and will therefore vary significantly over the pressure range. The resolution is better at lower frequencies.

In period counting, the gate time is equal to the number of counts of the sensor frequency divided by the actual frequency:

$$T_G(sec) = \frac{N_s}{F_s(Hz)}$$

Precise gate times are difficult to achieve since the sensor frequency must be known to determine the actual gate time. A simple option for determining the gate time is to set N_s to a constant. This results in gate times that can vary significantly over the frequency range of F_s . Figure 12 shows gate time as a function of sensor frequency for a number of values of N_s . The sensor resolution using this method can be determined by substituting for $t(sec)$ in the above sensitivity equation:

$$R(psi) = \frac{F_s^2(Hz^2)}{F_R(Hz)N_s(counts)S_{PP}(Hz/psi)}$$

Note that the equation shows resolution improving with larger N_s (longer gate times) and higher time base frequencies. The equation also shows that the resolution improves at lower sensor frequencies. This results in a resolution which approaches % of reading rather than the fixed resolution (% FS) of direct frequency counters (See Figure 13).

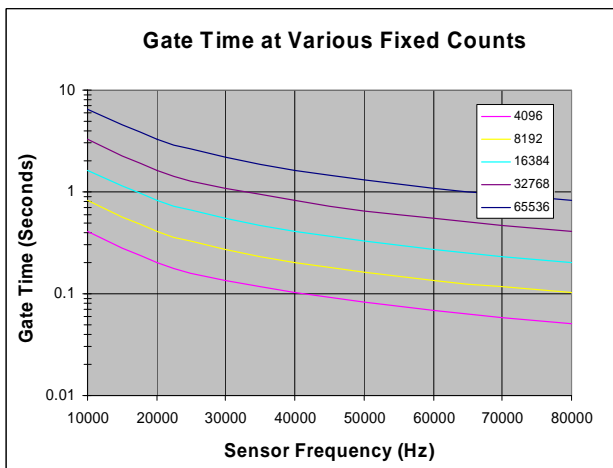


Figure 12. In a period counter where N_s is constant, the gate time will vary significantly over the sensor frequency range.

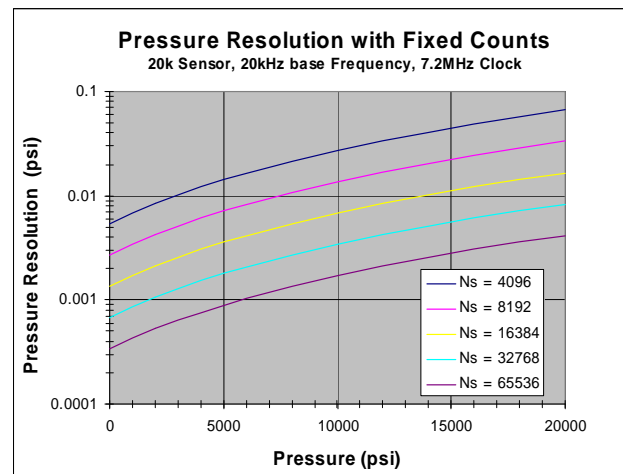


Figure 13. The pressure resolution is better at lower pressures with a fixed-count period counter.

If variable gate times are a problem, N_s may be chosen dynamically based on the previous frequency measurement, or a separate timer may be used to arm the counter to terminate on the next transition of F_s (Figure 14). The downside to this approach is a more complex counter, and the need to store both N_s and N_R , or to compute the ratio of the two prior to storage. Quartzdyne's Digital transducer uses the latter approach, reporting the divided ratio of N_s and N_R . The gate time is set by the end user based on the query rate.

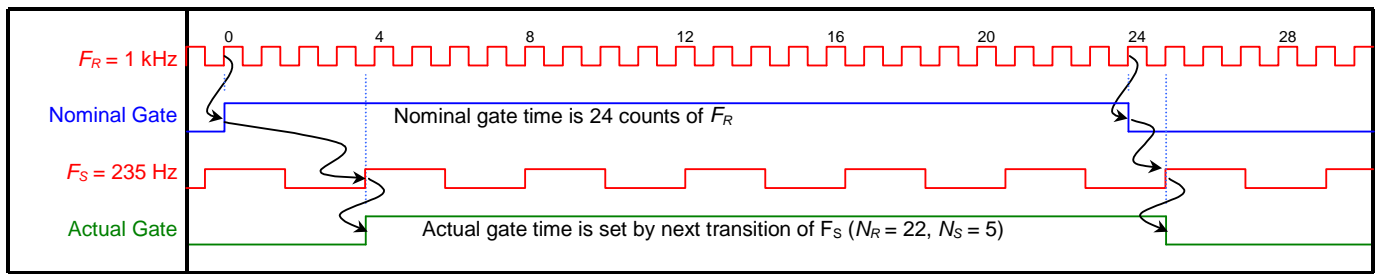


Figure 14. A fixed gate time can be achieved with a period counter by setting a nominal gate as in a Direct Frequency Counter, but controlling the actual gate as in a Period Counter. Both N_R and N_S are variable with this counting method.

4.3 Temperature Resolution Requirements

The temperature sensor included in QUARTZDYNE® Pressure Transducers has sensitivity S_{TT} between 100 Hz/°C and 300 Hz/°C over the various operating temperature ranges. Adequate temperature resolution may be achieved by using the same counting method and gate time for both temperature and pressure frequencies. A counting method which provides pressure resolution of 0.1 psi will provide temperature resolution of 0.002°C. The primary purpose of the temperature sensor is to provide temperature compensation for the pressure sensor. At the extremes of low pressure-high temperature and high pressure-low temperature, the pressure sensor may have a sensitivity to temperature S_{PT} as high as 100Hz/°C. In this case the pressure resolution will be dominated by the temperature frequency counter.

Note that the temperature frequency decreases with increasing temperature, while the pressure frequency increases with pressure. In a fixed count system the shortest combined gate time will be at high pressure and low temperature, while the longest combined gate time will be at low pressure and high temperature.

4.4 Effect of Sensor Frequency Jitter on Resolution

Thus far, the discussions of resolution have ignored the effect of sensor frequency jitter. Jitter is the small variation in the period, $1/f$, of the sensor signal. The jitter (typically ± 100 nanosecond) is due to the cross talk between the pressure and temperature signals. While the effect of jitter is minimized by counting multiple periods of the signal, sensor jitter may still limit useful pressure resolution, particularly when a very high frequency time base is used. Note that the counter-induced jitter using the 7.2MHz reference signal is ± 140 nanoseconds. The following equation includes the effects of both the counter and the sensor jitter:

$$R(\text{psi}) = \frac{F_s}{S_{PP}} \left(1 - \frac{T_G}{T_G + T_J + \frac{1}{F_R}} \right),$$

where

- R = Resolution (psi)
- F_s = Sensor Frequency (Hz)
- S_{PP} = Sensitivity (Hz/psi) (see specifications on transducer datasheets)
- T_G = Gate time (sec)
- T_J = Sensor pressure jitter (sec)
- F_R = Time base frequency.

Including the effect of sensor jitter results in the effective resolution shown in Figure 15. The results of the previous discussions can be duplicated by setting $T_J = 0$. Note that at 7.2 MHz, the time base and sensor have nearly equal jitter. At lower time base frequencies (1-4 MHz) the time base jitter is the limiting factor; at higher time base frequencies (such as 16 MHz), the sensor jitter will dominate.

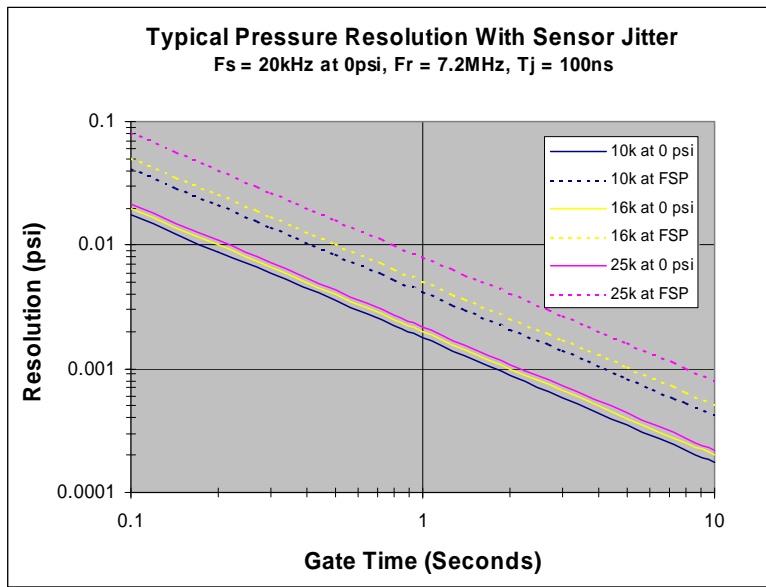


Figure 15 . Effect of Sensor Jitter on Pressure Resolution.

4.5 Reference-Based Counting

Downhole Transducers have a reference frequency output. This output is approximately 7.2 MHz and has good thermal coupling to the temperature and pressure crystals. Using the internal reference frequency as the time base for the frequency counters provides digital temperature compensation of the time base. To achieve the same effect using an external time base, the entire tool would need to be calibrated as a unit. Even then, the thermal coupling between the temperature sensor and the time base crystal will not be as good. In addition, if the time base is changed, the tool must be calibrated again. A 40 ppm error in the user's time base frequency will result in approximately 1 psi error in the transducer. By using the transducer reference as the time base for the counter, the pressure transducer becomes a fully contained transfer standard.

Two sets of coefficient files are provided with QUARTZDYNE® transducers that have a reference frequency output. These are referred to as standard and reference-based coefficients. The standard coefficients assume that a frequency counter with its own calibrated time base is used to count frequency. Frequency errors in the time base will directly effect the transducer frequency readings and consequently the calibrated transducer output.

The reference-based coefficients assume that the frequency counter uses the reference frequency of the transducer as its time base. At each pressure/temperature point there is a unique combination of the ratio of F_p / F_r and F_t / F_r . This ratio (scaled by 7.2E6) is used as the input to the curve fit. The curve fit provides digital temperature compensation for changes in F_r . To make the ratios "feel" more like frequencies, we arbitrarily multiply them by a constant 7.2 MHz. This gives an output frequency that does not yet reflect the digital compensation. It will differ from the true frequency as shown:

$$F_{true} = F_{apparent} \times \frac{F_r}{7.2 \text{ MHz}} .$$

F_r may vary from 7.2 MHz by as much as ± 7.0 kHz depending on the transducer and operating temperature. In our calibration system, we measure all three frequencies with a true frequency counter and calculate the apparent frequency as follows:

$$F_{apparent} = F_{true} \times \frac{7.2 \text{ MHz}}{F_r} .$$

$F_{apparent}$ should be used when computing reference-based coefficients during recalibration. If a reference-based counter is used to recalibrate, this is automatic.

5 CALIBRATION

5.1 Transducer Calibration Data

The performance demonstrated during calibration of each transducer is shown in the Transducer Calibration Chart supplied with each transducer. The chart shows the deviation of each point from the calibration equation using the coefficients calculated for the transducer. Figure 16 shows the performance typical of QUARTZDYNE® Pressure Transducers. The residual error at all temperatures is less than 0.01% of full scale (FS). This includes any errors in the linearity correction, repeatability, hysteresis, and temperature errors. Note that the residual error compares the transducer to the calibration standard; the error of the standard must be added to the residual error shown. Quartzdyne's calibration standard is a deadweight tester that is accurate to ±0.01% of reading.

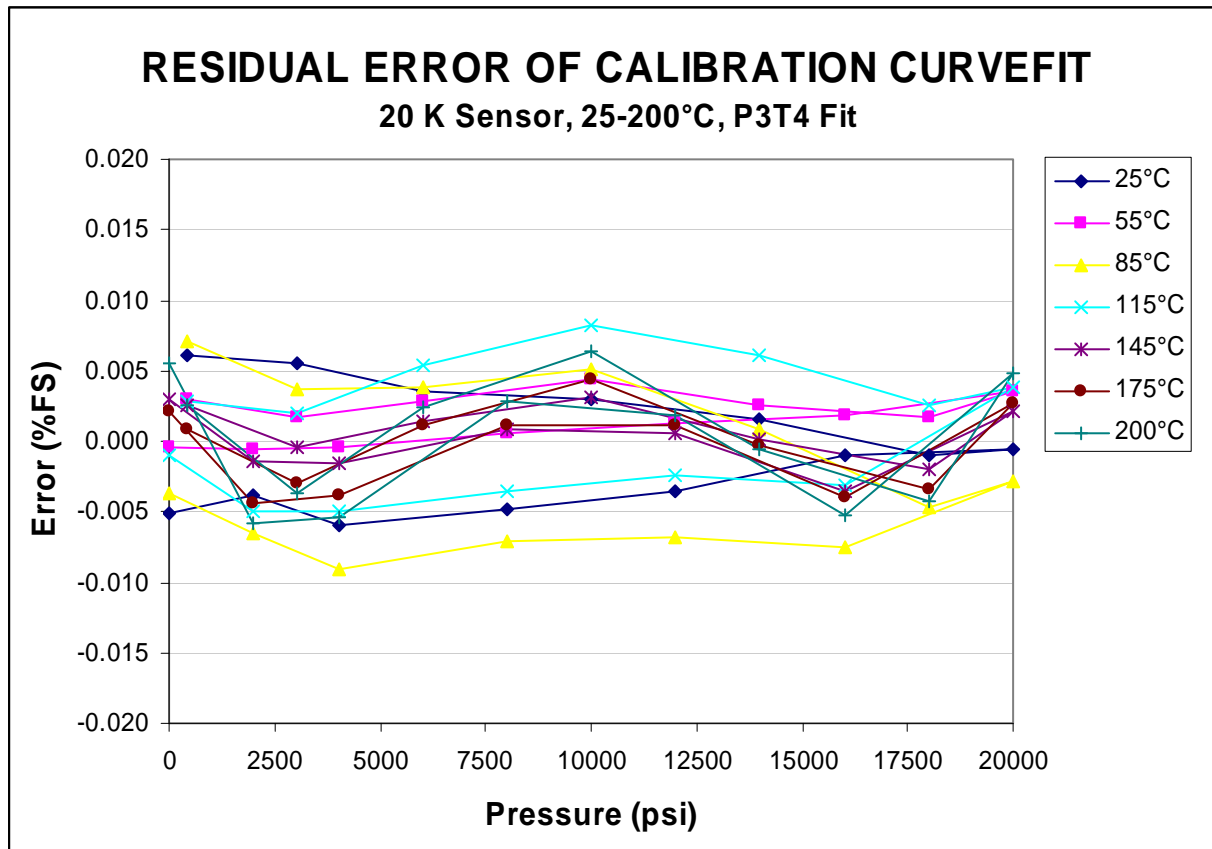


Figure 16 . Calibration curve typical of QUARTZDYNE® Pressure Transducers.

5.2 Traceability of Calibration

Calibration of QUARTZDYNE® Pressure Transducers is traceable to the U.S. National Pressure Standards maintained by the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS).

5.3 Typical Values of Corrections Used in Calibration

Achieving the 0.01% of reading accuracy specification of our pressure calibration standards requires that all potential sources of error in calibration are identified. In the Quartzdyne calibration laboratory the atmospheric pressure reference is either a Mensor 2104 or 1550D Digital Pressure Gauge. The height of the head is measured to within 0.25 inches [6.35 mm], providing a head pressure correction to 0.008 psia [0.570 mbar]. The pressure generated by our DH Instruments Model 5306 and Model 50000 Class S fundamental (deadweight) pressure standards includes corrections for local gravity, air buoyancy, and pressure and temperature effects on the cross-sectional area of the pistons. With these corrections, the pressure generated by the pressure standards is accurate to 0.01% of reading. The typical values used in calibration at our facility are "non-standard" values due to our 4251 ft [1296 m] elevation.

P_{atm}	=	12.6 psi [869 mbar] (measured continuously during calibration)
P_{head}	=	0.033 psi/in [0.897 mbar/cm]
Local gravity	=	9.797930 m/s ² (interpolated from National Geodetic Survey data http://www.ngs.noaa.gov/)
air density	=	1.015 gm/cm ³ (buoyancy correction is 23 ppm less than standard)
Piston pressure effect	=	60 ppm at 10,000 psi [689 bar]
Piston temperature effect	<	50 ppm typical

5.4 Calibration Procedure

QUARTZDYNE[®] Pressure Transducers provide three output signals: a pressure signal (10 to 100 kHz), a temperature signal (10 to 100 kHz) and a 7.2 MHz reference signal. The signals are measured with a frequency counter, and the temperature-compensated pressure is computed from the frequencies using a polynomial equation and a set of coefficients.

The unique coefficients for each transducer are determined in calibration. The frequencies are measured at a number of known pressures at several different temperatures. The coefficients are computer-generated (using matrix algebra) from the frequency and pressure data recorded during the calibration. Included with each transducer is a floppy disk containing the original calibration data, the coefficient files, and various demonstration programs including a program to generate coefficients from user supplied calibration data.

The requirements for control and measurement of pressure, temperature, and frequency during calibration are discussed in the sections that follow.

5.5 Pressure Control Required for Calibration

QUARTZDYNE[®] Pressure Transducers measure absolute pressure. The pressure that the transducer senses during our calibration is the sum of the atmospheric pressure, head pressure, and the pressure generated by the (gauge) pressure source.

The calibration equation is a polynomial in temperature and pressure. The order of the equation determines the number of different pressures and temperatures required in the calibration. As a minimum, at least one more data point is required than the order of the fit for each variable. Some redundancy in the pressure and temperature measurement is recommended. For example, in our calibrations we typically apply a sequence of pressures at each of five or six temperatures. Four temperatures are required for a third order fit, five for a fourth order. At each temperature, measurements are made at ambient atmospheric pressure, at 400 psia [27.6 bar], and at least every 20% of range up to full scale. The pressures are typically applied in the sequence:

ambient, 20%, 60%, 80%, 100%, 90%, 70%, 40%, 400 psia.

It is not necessary to follow this exact procedure, but this sequence has several advantages:

- (1) It provides a large enough sample of different pressures (four are required for a third order curve fit; nine unique pressures are used) without excessive repetition.
- (2) Two low pressure points show the zero return. (The lowest pressure at which our automated fundamental pressure standard provides 0.01% of reading accuracy is 400 psia [27.6 bar]; at lower pressures the error is a constant 0.02 psia [0.00138 bar].)
- (3) It provides the same number of increasing and decreasing pressure data points; the curve fit will be forced through the center of any apparent hysteresis loop.

5.6 Temperature Control Required for Calibration

The pressurization process described above must be performed at several temperatures as dictated by the fit order. The temperature need not be measured (unless a calibrated temperature output is desired), but it must be stable. A

temperature chamber with stability of at least 0.25°C is recommended. Monitoring the temperature sensor crystal will provide an indication of the thermal stability of the transducer; when the temperature sensor has stabilized, a pressure calibration cycle may begin. Note that the temperature sensitivity varies from approximately 115 Hz/°C at -40°C to 260 Hz/°C at 200°C.

It is desirable that the temperature of the three crystals in the transducer be as uniform as possible. Beware of thermal gradients that can develop along the length of the transducer as these may cause significant errors in the calibration. Figure 17 shows possible sources of temperature gradients that may occur in a calibration oven or bath. The error will be most pronounced in the areas of high thermal sensitivity as shown in Figure 7.

At least four temperatures are dictated by a third-order temperature dependence. At least five temperatures are required for a fourth order dependence. The six- to seven-temperature calibration done by Quartzdyne provides adequate redundancy. It is recommended that the entire temperature range of use be covered in the calibration. Specifications of the transducer outside the factory calibrated temperature range are not guaranteed.

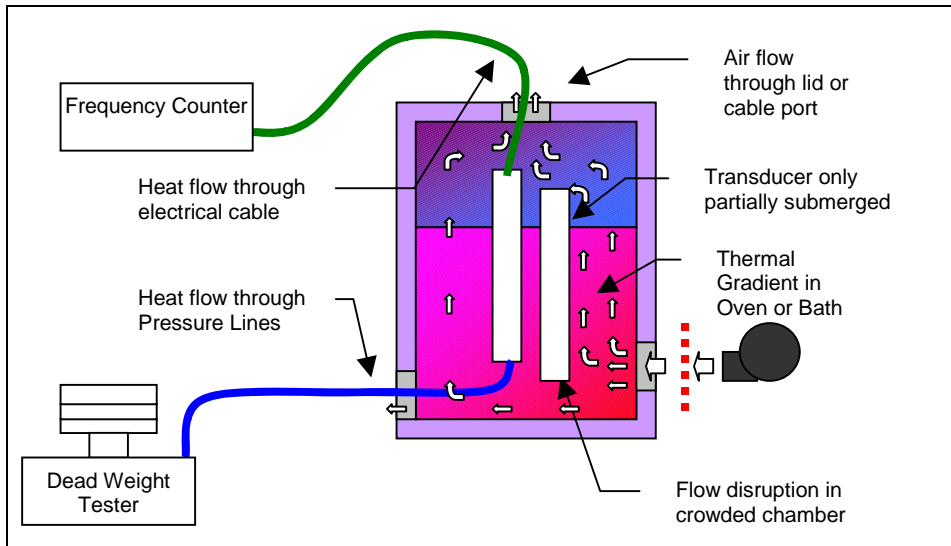


Figure 17. Possible sources of temperature gradients in a calibration oven or bath.

5.7 Frequency Measurement during Calibration

In addition to proper pressure and temperature control, calibration requires measurement of the transducer's output frequencies. Normally this is done with the frequency counter that is to be used in the field. The QUARTZDYNE® Series I may be used to measure the transducer frequencies if the end tool will be using the transducer reference frequency as the time base. At Quartzdyne, Agilent 53131A frequency counters are used to measure the absolute frequency of all three signals (Figure 18). The counters are linked to an Agilent 58501A GPS receiver that provides frequency accuracy to better than 1×10^{-12} . Reference-based coefficients are generated by mathematically computing the reference-based frequencies per the equation:

$$F_s(\text{reference-based}) = 7.2E6 \times \frac{F_s(\text{true})}{F_r(\text{true})}$$

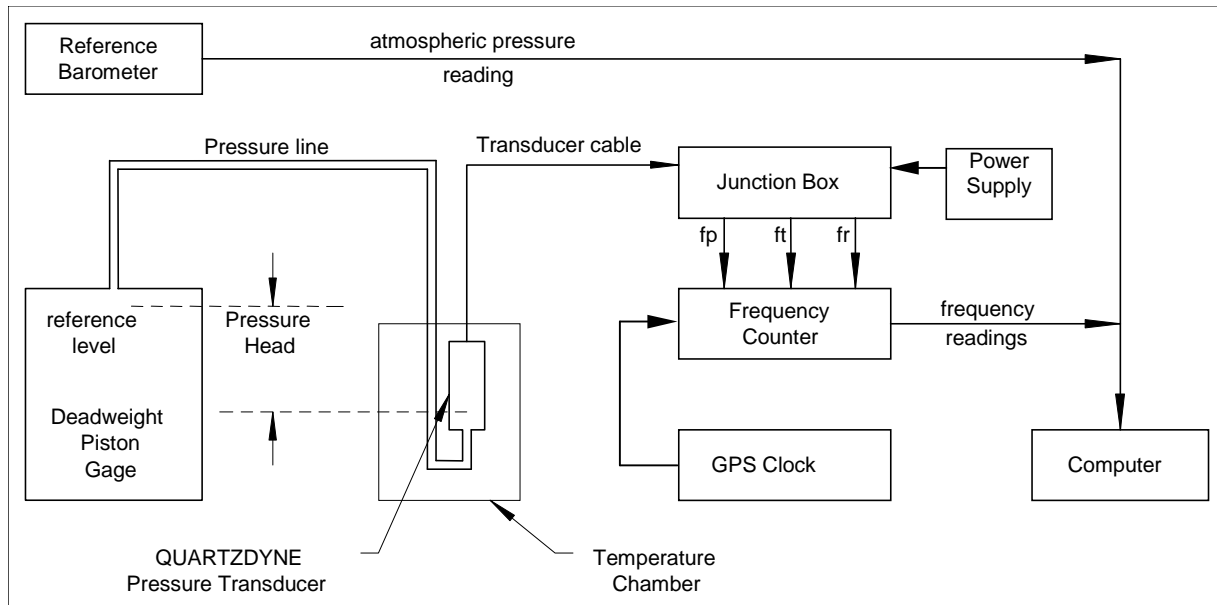


Figure 18. Transducer Calibration

6 Curve fit Algorithm

QUARTZDYNE® Pressure Transducers are calibrated using a two input polynomial Least Mean Squared (LMS) curvefit. The inputs to the polynomial are scaled versions of the pressure and temperature frequencies. To calibrate a transducer, data must be taken at appropriate temperatures and pressures, recording Pressure, Temperature, Pressure Frequency, and Temperature Frequency. Temperature is not used in the pressure calibration, it is only used to calculate separate temperature coefficients if desired. The minimum number of data points is a function of the number of coefficients used. For a third-order fit in pressure, and a fourth-order fit in temperature, 20 coefficients are generated. This requires at least four different pressure readings at each of five temperatures. Redundant data points result in better interpolation between calibration points. Distributing the points evenly over the pressure and temperature range improves the quality of the solution.

Once the calibration file has been created, the frequencies are pre-scaled using the following equation:

$$x = m(f - f_0),$$

where m is a scaling factor (usually 0.01) and f_0 is the frequency at an ambient data point. Prescaling is used to reduce round-off errors that occur during computation. These numbers may need to be modified depending on the requirements of the matrix solution routines. The scaled data is used to compute the LMS coefficients.

The software distribution disk contains programs for computing and creating coefficient files using these algorithms. The algorithm used in the programs is described below.

6.1 Derivation of LMS Fit

Assume that a function can be described by the summation of a set of coefficients, C_i , multiplying arbitrary functions, F_i , of its input variables. These functions will typically be polynomials but could just as easily be exponentials or other functions. The calculated output Z_c will be

$$Z_c = \sum_{i=1}^S C_i f_i .$$

Next define an error term $e(n)$ equal to the difference between the calculated and desired output $z(n)$ for an arbitrary sample n ,

$$e(n) = z_c(n) - z(n) = \sum_{i=1}^S c_i f_i(n) - z(n) .$$

The squared error is the square of this summed over N samples of the input function:

$$E^2 = \sum_{n=1}^N e^2(n) = \sum_{n=1}^N \sum_{i=1}^S [c_i f_i(n) - z(n)]^2 .$$

Minimize the squared error by taking the partial derivative with respect to each coefficient and setting it equal to zero;

$$\frac{\partial E^2}{\partial c_k} = 2 \sum_{n=1}^N \sum_{i=1}^S [c_i f_i(n) - z(n)] f_k(n) = 0 .$$

With a little bit of algebra this can be reduced to:

$$\sum_{i=1}^S c_i \sum_{n=1}^N f_i(n) f_k(n) = \sum_{n=1}^N z(n) f_k(n) .$$

By varying k from 1 to S we define S equations in S unknowns which can be solved using standard matrix algebra techniques.

6.2 Calculating the LMS Fit

The inputs to the solution routine are as follows:

- $X[N]$ - Prescaled Pressure Frequencies
- $Y[N]$ - Prescaled Temperature Frequencies
- $Z[N]$ - True Pressure
- $S1$ - Fit order in X (Typically 3)
- $S2$ - Fit order in Y (Typically 3)
- S - $(S1 + 1) * (S2 + 1)$
- N - Number of data points ($>S$).

The outputs are:

- $C[S]$ - Calibration Coefficients
- $R[N]$ - Calibration Residuals.

For the computation, we need to compute three additional matrices. First we need to create the powers of XY matrix $F[N,S]$ which defines the polynomial trial function to be used in the LMS fit for each data point:

$$F[N,S] = \begin{bmatrix} x_1^0 y_1^0 & x_1^0 y_1^1 & x_1^0 y_1^2 & \dots & x_1^{S1} y_1^{S2} \\ x_2^0 y_2^0 & x_2^0 y_2^1 & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ x_N^0 y_N^0 & \cdot & \cdot & \cdot & x_N^{S1} y_N^{S2} \end{bmatrix} .$$

Next create the resultant vector $A[S]$,

$$A[S] = Z[N]F[N,S] .$$

And the crossproduct matrix $B[S,S]$,

$$B[S,S] = F^{Tm} [S,N]F[N,S] .$$

Note that $B[S,S]$ is diagonally symmetric ($B[i,j] = B[j,i]$) so only one half of the matrix must be calculated. The simultaneous equations described by

$$A[S] = B[S,S]C[S]$$

are the equations of the LMS algorithm described above. The coefficient matrix $C[S]$ can be found using LDL^T Gaussian elimination or other appropriate solution methods,

$$C[S] = B^{INV} [S,S]A[S] .$$

The calibration residuals are calculated from $F[N,S]$, $C[S]$, and $Z[N]$,

$$R[N] = F[N,S]C[S] - Z[N] .$$

The following BASIC subroutines implement the solution method described. C versions of the same are included in the demonstration disk.

6.3 Subroutines for Calculating an LMS Polynomial Fit

```

SUB LMSPolyFit (x() AS DOUBLE, y() AS DOUBLE, z() AS DOUBLE, c() AS DOUBLE, r() AS
DOUBLE, npts AS INTEGER, n1 AS INTEGER, n2 AS INTEGER)
  DIM errflag AS INTEGER
  n = (n1 + 1) * (n2 + 1)
  REDIM f(npts, n), a(n), b(n, n) AS DOUBLE
  '
  '   CREATE POWERS OF XY MATRIX F(npts,n)
  '
  FOR k = 1 TO npts
    f(k, 1) = 1#
    FOR i = 1 TO n2
      f(k, i + 1) = f(k, i) * y(k)
    NEXT i
    FOR i = i TO n - 1
      f(k, i + 1) = f(k, i - n2) * x(k)
    NEXT i
  NEXT k
  '
  '   Create A[n] = Z[npts]*F[npts,n]
  '
  FOR i = 1 TO n
    a(i) = 0#
    FOR k = 1 TO npts
      a(i) = a(i) + z(k) * f(k, i)
    NEXT k
  NEXT i
  '
  '   CREATE B[n,n] = TRN( F[npts,n] ) F[npts,n]
  '
  FOR i = 1 TO n
    FOR j = 1 TO i
      b(i, j) = 0#
      FOR k = 1 TO npts
        b(i, j) = b(i, j) + f(k, i) * f(k, j)
      NEXT k
      b(j, i) = b(i, j)
    NEXT j
  NEXT i
  '
  '   Solve matrix equation A[n] = B[n,n]C[n] for C[n]
  '
  CALL Solve(a(), b(), c(), n, errflag)
  IF errflag <> 0 THEN ' MATRIX SOLUTION DIDN'T WORK
    BEEP
    PRINT "Ill conditioned data, no solution was found'"
    STOP
  END IF
  '
  '   COMPUTE FIT RESIDUALS
  '
  FOR k = 1 TO npts
    r(k) = 0#
    FOR i = 1 TO n
      r(k) = r(k) + f(k, i) * c(i)
    NEXT i
    r(k) = r(k) - z(k)
  NEXT k
END SUB

```

```

SUB Prescale (x() AS DOUBLE, m AS DOUBLE, X0 AS DOUBLE, npts AS INTEGER)

```

```

DIM n AS INTEGER
FOR n = 1 TO npts
  x(n) = m * (x(n) - X0)
NEXT n
END SUB

SUB Solve (a() AS DOUBLE, b() AS DOUBLE, c() AS DOUBLE, n AS INTEGER, errflag AS
INTEGER)
  REDIM d(n) AS DOUBLE

  '
  ' DECOMPOSE B (LDLt GAUSSIAN ELIMINATION)
  ' Assumes B is a symmetric matrix - A and B are modified
  '
  errflag = 0
  IF b(1, 1) = 0 THEN GOTO Errexit
  d(1) = 1 / b(1, 1)
  FOR i = 2 TO n
    b(i, 1) = b(i, 1) * d(1)
  NEXT i
  FOR i = 2 TO n
    FOR j = 1 TO i - 1
      b(i, i) = b(i, i) - b(j, j) * b(i, j) * b(i, j)
    NEXT j
    IF b(i, i) = 0 THEN GOTO Errexit
    d(i) = 1 / b(i, i)
    FOR j = i + 1 TO n
      FOR k = 1 TO i - 1
        b(j, i) = b(j, i) - b(k, k) * b(i, k) * b(j, k)
      NEXT k
      b(j, i) = b(j, i) * d(i)
    NEXT j
  NEXT i

  '
  ' REDUCE COLUMN VECTOR
  '
  FOR i = 2 TO n
    FOR j = 1 TO i - 1
      a(i) = a(i) - b(i, j) * a(j)
    NEXT j
  NEXT i

  '
  ' BACKSUBSTITUTE TO OBTAIN C
  '
  FOR i = 1 TO n
    c(i) = a(i) * d(i)
  NEXT i
  FOR i = n - 1 TO 1 STEP -1
    FOR j = i + 1 TO n
      c(i) = c(i) - c(j) * b(j, i)
    NEXT j
  NEXT i
  EXIT SUB
Errexit: 'Zero Diagonal Term found - Can't solve with Gauss elimination
  errflag = 1
END SUB

```