AN OVERVIEW OF DYNAMIC PRESSURE MEASUREMENT CONSIDERATIONS

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March, 2010

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I. INTRODUCTION

The subject of precision measurement of dynamic pressures has been discussed in great detail by many authors and researchers. Each have gone into depth discussing both theoretical and experimental results describing the complexities of dynamic pressure. Unfortunately, due to the nature of the subject, and its inherent complexity, it is difficult to find a single source covering the entire subject on a broad, high level scope. The focus of this paper is to discuss practical guidelines and considerations for measuring dynamic pressures.

With pressure measurement equipment technology as it currently stands, pressure scanners are capable of reaching very high scan rates (in excess of 600 Hz). However, the pressure scanner is not the limiting factor when determining the maximum desired scanning speed. There is little benefit from recording the pressure within a system at a higher frequency than a pressure can be accurately transmitted through the tubing of the system.

When high frequency dynamic pressures are to be measured, there are many factors that should be considered. Primary among them are tubing length and tubing diameter. Additionally, temperature, the internal volume of the transducer, the geometric layout of the tubing and the type of tubing are some other considerations. Unfortunately, unless very low frequency dynamic pressures are being measured (below 1 Hz) these considerations should be accounted for. All of these variables combine to affect the measured pressures. By the time the sample pressure waves reach the measuring device, they can potentially be skewed in three forms. The pressure waves could be shifted, altering any time correlations made or the magnitude of the pressure waves could be distorted giving erroneous measured pressures. Finally, if a resonance has developed within the tubing, false data could be measured masking true data.

II. EFFECTS

As previously mentioned, the effects variables make on the measured dynamic pressure can be described by one of three forms of distortion; resonance, pressure wave shift or amplitude change. Any of these three alterations to the waves will obviously distort the pressure being measured. There are however considerations that can be made to account for all three of these phenomena. In order to complete the required calculations, reference figures 1, 2, 3 & 4 for the internal volumes of the most popular Scanivalve products.

i. Resonances

When dealing with a resonance within the tubing, Bergh [Ref 1] tells us that a resonance will occur if the following equation is true:

$$\cot g\left\langle \frac{\upsilon L}{a_0} \right\rangle = \gamma \frac{V_v}{V_t}\left(\sigma + \frac{1}{k}\right)\left(\frac{\upsilon L}{a_0}\right)$$

By deduction, we can see that when $V_v = 0$ or $V_v = \infty$ (although neither are applicable or possible) this equation results in the resonance formulae for a closed or open organ pipe. If this step is completed and it is found that no resonance will be present, further consideration of resonances can be eliminated.

However, if it is determined that a resonance will be present or is very close to existing then more considerations must be made to preserve the validity of the data. What Rajan [Ref 6] discussed and Tijdeman [Ref 8 & 9] explains in his expansion Bergh's work is that simple alterations to the system can have a significant impact on reducing or eliminating a resonance. By simply installing a restrictor in the system, installing a physical damper (a filter or even something as simple as a piece of yarn inserted in the tube), or even changing the length of the tubing slightly a resonance can be eliminated from the system entirely. Bergh & Tijdeman [Ref 1 & 8] discussed in great detail the effects of a change in tubing diameter (such as a restrictor) while Rajan [Ref 6] covers the subject from a more empirical perspective.

ii. Phase Shift

Unlike a resonance, phase shift can never be completely eliminated. Whereas resonances can be eliminated by altering the system in some way, phase shift must be accounted for and removed through theoretical calculations or empirical testing. To some degree, phase shift can be minimized by careful design of the system. Depending on the desired level of accuracy and the frequency of the input pressure, a phase shift can be reduced to a point where it does not need to be considered.

With that said, only situations needing very accurate time correlation should be concerned with the calculation of the phase shift. If it is determined that phase shift should be calculated, the following formula developed by Bergh & Tijdeman [Ref 1] from the Navier-Stokes equation should be used.

$$u = \frac{i}{a_0 \rho_s} \sqrt{\frac{J_0\langle\alpha\rangle}{J_2\langle\alpha\rangle}} \sqrt{\frac{\gamma}{n}} \left\{ \frac{J_0\left\langle \frac{\alpha r}{R} \right\rangle}{J_0\langle\alpha\rangle} - 1 \right\} \left\{ A \exp\left[\frac{\omega x}{a_0} \sqrt{\frac{J_0\langle\alpha\rangle}{J_2\langle\alpha\rangle}} \sqrt{\frac{\gamma}{n}} \right] - B \exp\left[- \frac{\omega x}{a_0} \sqrt{\frac{J_0\langle\alpha\rangle}{J_2\langle\alpha\rangle}} \sqrt{\frac{\gamma}{n}} \right] \right\}$$

* where A, B & n are constants

The output of this formula will generate the phase shift in degrees. This can then be converted into a velocity using the following formula:

$$\bar{u} = u e^{i\omega t}$$

iii. Amplitude Distortion

As with phase shifts, distortions to the amplitude of the pressure waves can never be completely eliminated. Again, many factors contribute to the total distortion of the pressure amplitude. Altering these variables can in some cases allow the amplitude distortions to be negligible. In most cases however, the amplitude distortion of the pressure wave should be accounted for. The following formula is derived from the Navier-Stokes formula by Bergh [Ref 1] and can be used to calculate the total distortion of the amplitude of the pressure wave.

$$p = A \exp\left[\frac{\iota x}{a_0}\sqrt{\frac{J_0\langle\alpha\rangle}{J_2\langle\alpha\rangle}}\sqrt{\frac{\gamma}{n}}\right] + B \exp\left[\frac{\iota x}{a_0}\sqrt{\frac{J_0\langle\alpha\rangle}{J_2\langle\alpha\rangle}}\sqrt{\frac{\gamma}{n}}\right]$$

* where A, B & n are constants

III. OTHER CONSIDERATIONS

As discussed earlier, there are several factors that control the pneumatic frequency response of a system. Of these, the primary two factors are the length and diameter of the tubing in the system. As the tubing length increases, the magnitude of the amplitude distortion rapidly begins to increase. Like the distortions to the amplitude of the wave, the total phase shift also quickly begins to increase as tubing length increases. Tubing diameter also has a significant impact on the frequency response of the system, however it is much less linear and predictable. As a generalization, larger diameter tubing allows for higher pneumatic frequency response. These two factors are the primary variables in determining the pneumatic frequency response of the system. Additionally, there are many other factors that effect the system. Tubing material is discussed by A.W. Rofail [Ref 7] in great detail, while Rajan [Ref 6] is quoted in his report stating, “It is observed that the limitations of the amplitude responses depend strongly on the geometrical layout of the tubing system”. It can be seen that the physical layout of a system may have a significant impact on its frequency response. Unlike many other factors, it can be very difficult to quantify the effects of geometric layout on the frequency response of the system.

Other factors that are much more quantitative are: temperature, atmospheric pressure, volume of the transducer, mean velocity of sounds, velocity across the entrance of the tube, specific heat ratio and the shear wave number. In order to generate accurate data, all of these factors must be taken into consideration. The equations provided in this paper will include these variables and provide accurate data however, there are other viable solutions. Probably the most simple and practical solution to these problems lie in software. Through the Australasian Wind Engineering Society (AWES), a piece of software called ‘DropTubes’ is available that predicts the response of systems given many of these variables. It is simple to use and provides accurate data quickly and easily. It can be found on their website at: http://www.awes.org/?section=products.

The final solution for eliminating errors generated by the pneumatic system is to individually calibrate and tune each pressure input of the system before use. This procedure can be very time consuming and requires special equipment. However, it can ultimately yield the most accurate data. It requires known frequencies to be input into each tubulation and then tuning the system to remove any resonance present and minimize phase shifts or amplitude distortions. The known offset can then be applied to the recorded data to produce accurate data. It is highly recommended that some form of calibration is performed when a system is installed, then repeated each time the system is altered or any variables change. System calibrations can be done several ways, however the most common method is to use a small speaker generating a known tone directed into the pressure measurement point.

IV. CONCLUSIONS

This has been a brief discussion of the variables effecting the pneumatic frequency response of a system. The most fundamental aspects of this problem allow for very simple solutions to be applied. However, reviewing the problem as a whole, including all of the contributing factors leads to a very complicated set of considerations and solutions. In order to realistically generate accurate data, some consideration must be made in any dynamic pressure measurement scenario. The most practical solution to the problem is through the use of software, although discrete empirical testing generally will lead to the most valid data. For an in-depth review of the subject Bergh and Tijdeman [Ref 1 & 8] cover the fundamentals of the subject in great detail. Many other reports have been authored based on Bergh and Tijdeman's original report [Ref 1] and all cover various expansions of the subject well.

V. APPENDIX

i. List of Symbols and Variables

$$A = \frac{P_j - P_{j-1}\exp\left(-\phi_j L_j\right)}{\exp\left(\phi_j L_j\right) - \exp\left(-\phi_j L_j\right)}$$

$$B = \frac{P_{j-1}\exp\left(-\phi_j L_j\right) - p_j}{\exp\left(\phi_j L_j\right) - \exp\left(-\phi_j L_j\right)}$$

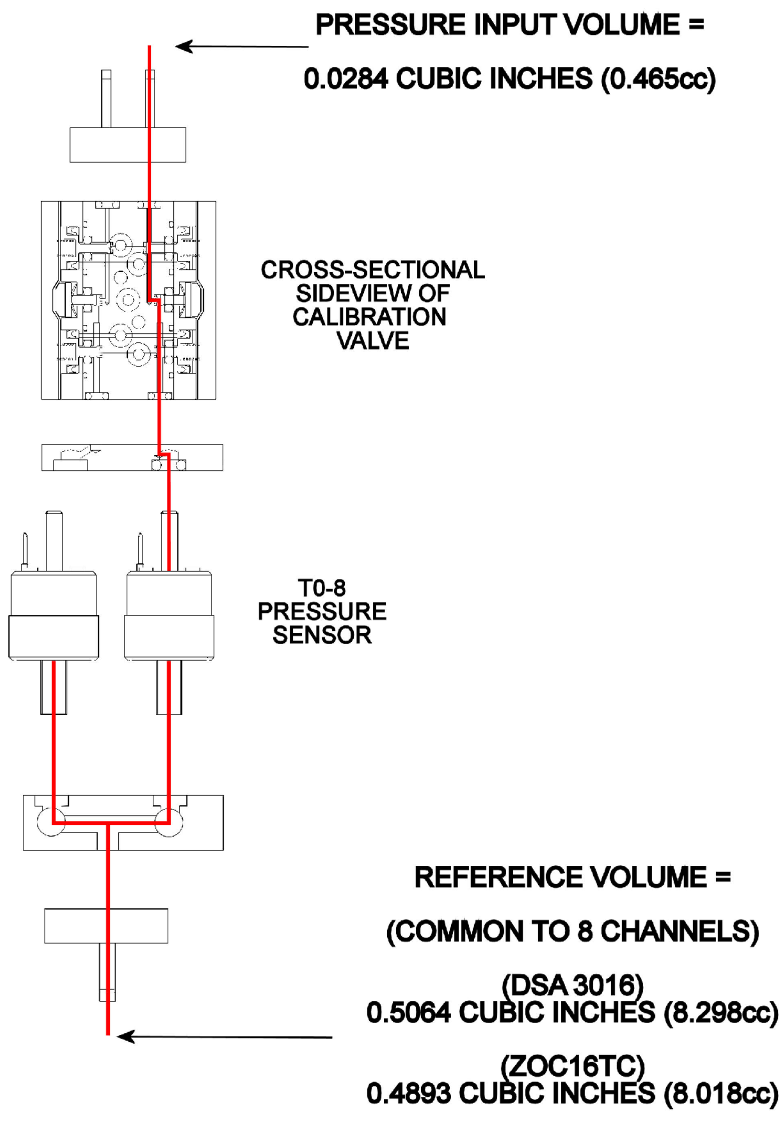
$a_0 = \sqrt{\frac{\gamma p_s}{\rho_s}}$	mean velocity of sound
C_p	specific heat at constant pressure
C_v	specific heat at constant temperature
g	gravity constant
$i = \sqrt{-1}$	imaginary number
J_n	Bessel function of first kind order n
k	polytropic constant for the volumes
L	tube length
m	mass flow
$n = \frac{1}{1 + \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{J_2\left\langle\alpha\sqrt{P_r}\right\rangle}{J_0\left\langle\alpha\sqrt{P_r}\right\rangle}\right)}$	type of polytropic constant p
p	amplitude of pressure distortion
$P_r = \frac{\mu g C_p}{\lambda}$	Prandtl number
r	co-ordinate in radial direction
R	tube radius
t	time
$\bar{u}$	velocity component in axial direction
u	phase shift
x	co-ordinate in axial direction
V_v	pressure transducer volume
V_t	volume of the tube

i. List of Symbols and Variables

$\alpha = i^{\frac{3}{2}} R \sqrt{\frac{\rho_s{}^{\upsilon}}{\mu}}$	shear wave number
$\phi = \frac{\upsilon}{a_0} \sqrt{\frac{J_0\langle\alpha\rangle}{J_2\langle\alpha\rangle}} \sqrt{\frac{\gamma}{n}}$	
$\gamma = \frac{C_p}{C_v}$	specific head ratio
λ	thermal conductivity
μ	absolute fluid viscosity
ρ_s	mean density
σ	dimensionless increase in transducer volume do to diaphragm deflection
υ	frequency

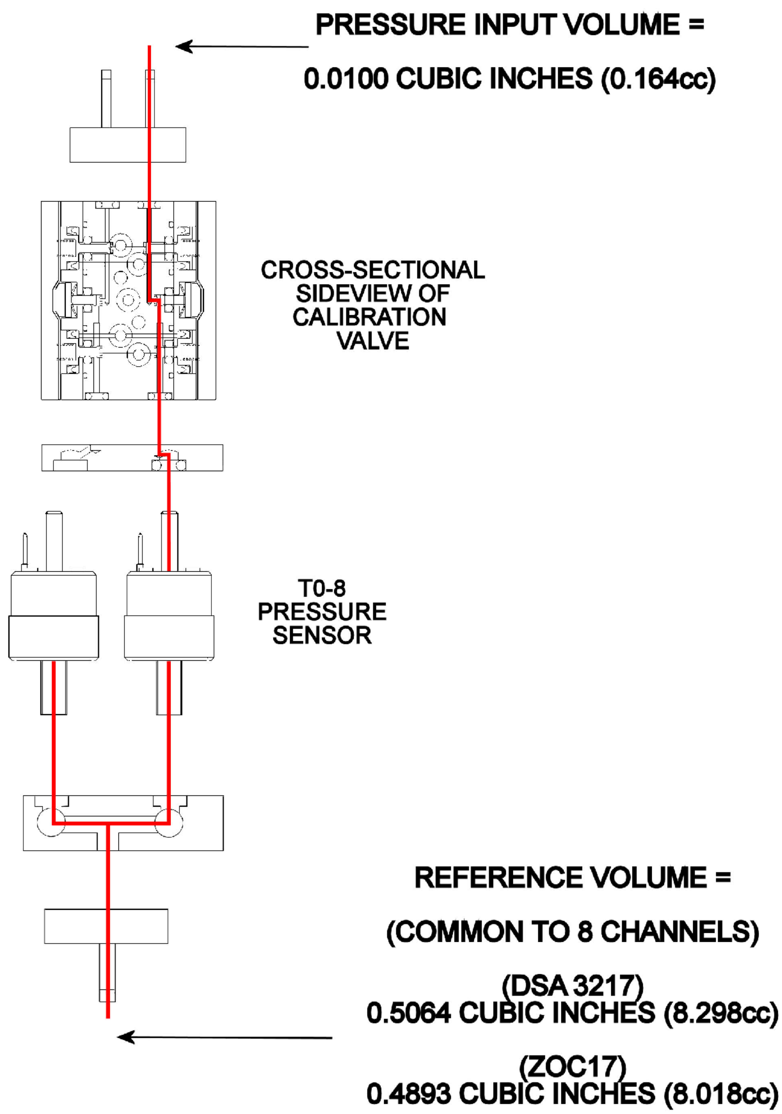
ii. Scanivalve Product Volume Studies

Figure 1 - DSA3016 / ZOC16TC Volumes



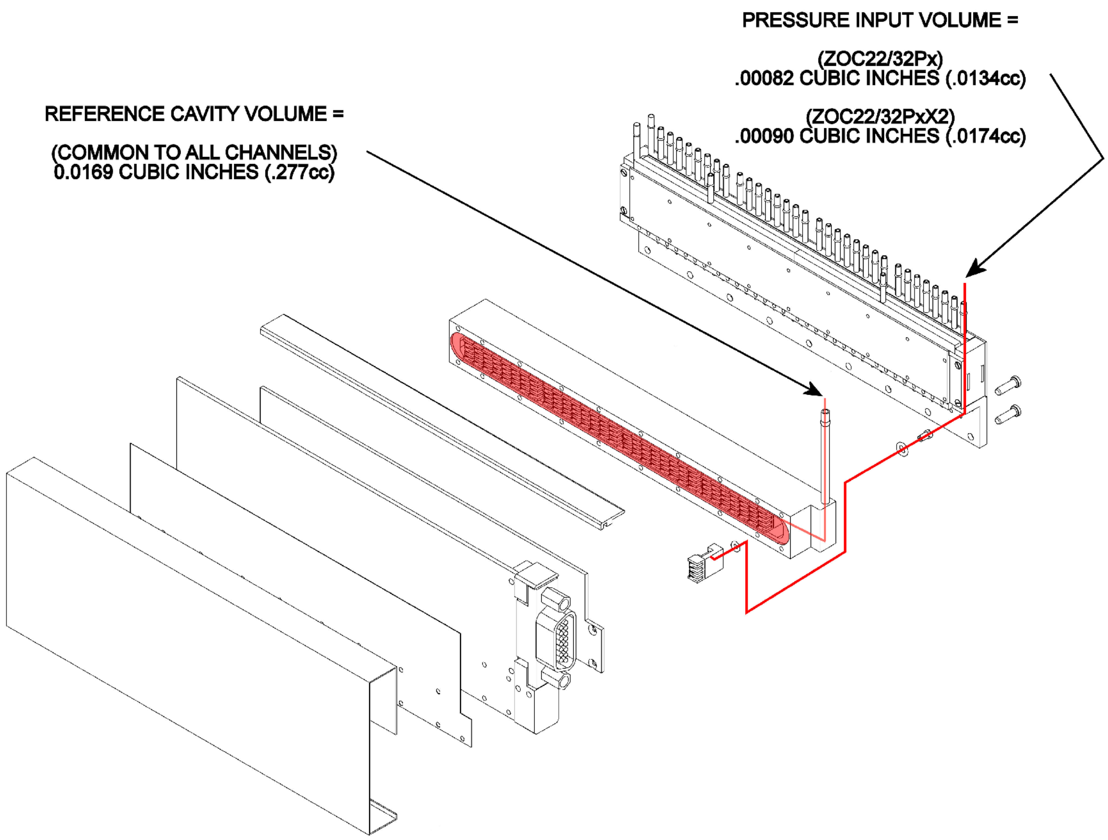
ii. Scanivalve Product Volume Studies

Figure 2 - DSA3217 / ZOC17 Volumes



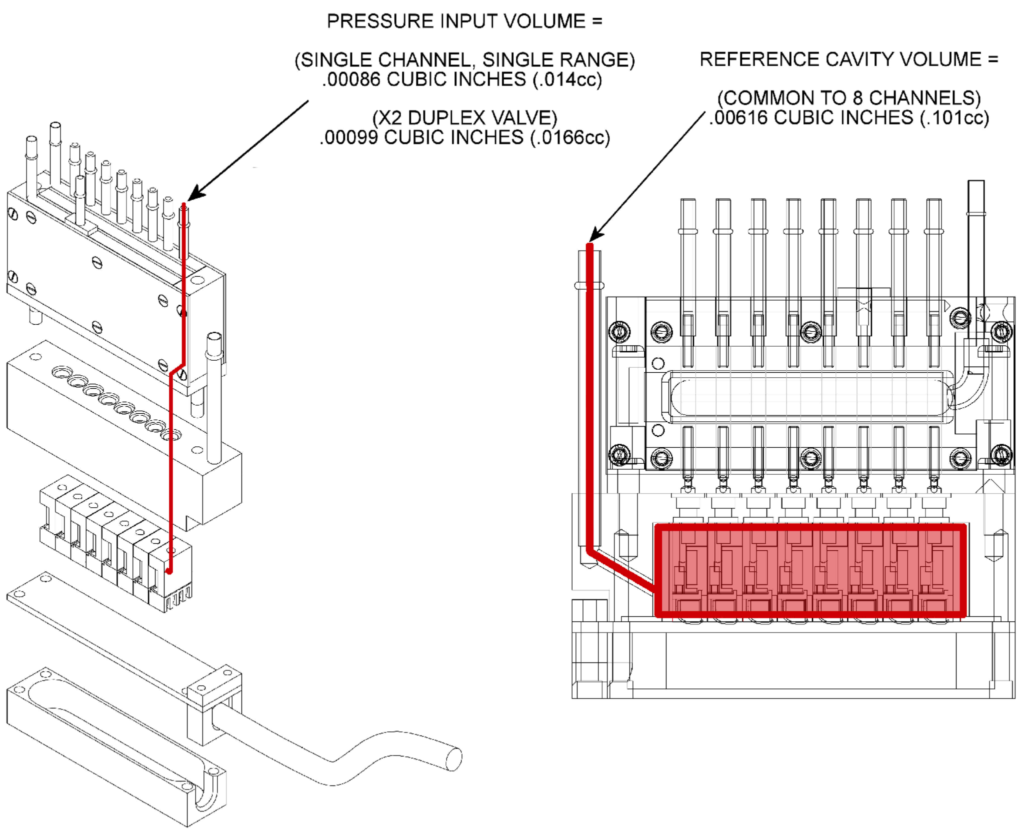
ii. Scanivalve Product Volume Studies

Figure 3 - ZOC22 Volumes



ii. Scanivalve Product Volume Studies

Figure 4 - ZOC23 / ZOC33 Volumes



iii. References

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