2012

Comparing FEM Transfer Matrix Simulated Compressor Plenum Pressure Pulsations to Measured Pressure Pulsations and to CFD Results

Keith Novak
keith.novak@trane.com

Jack Sauls

Comparing FEM Transfer Matrix Simulated Compressor Plenum Pressure Pulsations to Measured Pressure Pulsations and to CFD Results

Keith NOVAK[1]*, Jack SAULS[2]

Ingersoll Rand - Trane
Compressor Development and Technology
3600 Pammel Creek Road; La Crosse, WI 54601 USA

[1]Email: keith.novak@trane.com, Phone: 608-787-4105
[2] Email: jsauls@trane.com, Phone: 608-787-2517

* Corresponding Author

ABSTRACT

Improving efficiency of positive displacement compressors requires improving current computer compressor simulations to better model compressor behavior. This paper will specifically look at increasing fidelity of the 1D thermodynamic compressor simulation program by incorporating suction and discharge pulsations due to complex suction and discharge three dimensional (3D) plenum geometry. This method allows for quick pressure pulsation analysis and enables the design engineer to make changes early in the compressor development cycle. Finite Element Method (FEM) full harmonic analysis is used to calculate suction or discharge plenum's impedance transfer functions in the frequency domain. The impedance transfer functions are normalized to the FEM conditions and normalized impedance transfer functions are used to model all compressor operating speeds and operating conditions. The normalized impedance transfer functions are independent of mass flow, compressor speed, valve dynamics, sonic velocity, refrigerant density, refrigerant, bore size and stroke size which allow the 1D compressor simulation program to change any of these variables without have to solve for a new FEM impedance transfer function. We have also worked on a new way to include damping and phase shift between mass flow and pressure pulsations that better agrees with experimental and Computational Fluid Dynamics (CFD) results. Since some of this method is novel or may extend beyond the limits of linear acoustic analysis, it requires good agreement to compressor test results and to CFD results. The main part of the paper will show good agreement between simulated pressure pulsations to suction and discharge test results in a reciprocating compressor. The paper will also show our latest improvements in pulsation modeling to obtain better agreement to CFD results than the original comparison in Bilal *et al*.(2010).

1. INTRODUCTION

One of the currently used methods to calculating pressure pulsations in 1D compressor simulation program is to use the basic 1D acoustic elements in the four pole method (Zhou *et al*. 2001). The basic 1D acoustic element consist of mathematical equations for specific lengths and diameters of pipes, and small volumes to represent plenum sections. These sections are assembled to form a complete suction or discharge plenum. Early in the design stage this is sufficient to scope out the plenum design, but as the plenum is modeled in 3D geometry the geometry tends to diverge from the simple acoustic representation. CFD has been used to help define plenum geometry and calculate pressure pulsation from 3D geometry but CFD is time consuming and costly to perform. Commercially available pulsation software tends to over simplify the geometry and solve in the time domain. Working in the frequency domain simplifies the design process, reduces analysis time and gives the design engineer insight into how the plenum will respond to due to mass flows at compressor running harmonics frequencies. The FEM full harmonic analysis predicts how the acoustic waves travel and reflect in the 3D geometry. The design engineer can easily find resonance frequencies of the plenum and shift them away from operating frequencies. The hybrid pulsation method (Bilal *et al*. 2010) and improvements made in this paper use this FEM harmonic analysis to calculate the impedance transfer functions. FEM harmonic analysis is performed on the plenum at one operating condition and then the impedance transfer functions are normalized to FEM density and FEM sonic velocity. This method allows for a very simple and efficient way to incorporate the 3D plenum geometry into the 1D compressor simulation. The design engineer can run sensitivity studies or design of experiments to scope out performance gains or losses due to pressure. A companion paper discussing sensitivity studies or design of experiments done on a screw compressor is written by Sauls and Novak (2012). The design engineer has the ability to change the shape of plenum to control the shape of the pressure pulsation. An additional benefit of using this method is the results of the impedance transfer function can be used to determine the acoustic performance of the muffler or plenum. Confidence in this pulsation method will reduce the amount of CFD performed on the plenum and reduce design time of the compressor. CFD is now only required to validate the 1D compressor simulation program pulsations at key operating conditions.

2. IMPEDANCE TRANSFER FUNCTION

Wu and Zhang (1998) presented an improved method for calculating the four-pole parameters using 3D Boundary Element Method (BEM). We used this improved method to calculate the impedance transfer functions except we used FEM; FEM had similar results as BEM. Early in the plenum design stage, the harmonic analysis is performed to approximately 5 times the fundamental operating harmonic at a 5 Hz increment is usually sufficient. This allows the design engineer to modify the design quickly and determine the initial shape of the plenum. The first five pulsation harmonics affect compressor performance the most. The refrigerant density and sonic velocity at the operating condition of most interest is used in the FEM harmonic analysis. The impedance transfer functions are the pressure outputs of the FEM harmonic analysis divided by the FEM harmonic excitation flow load at each solved frequency. The impedance transfer functions are calculated at the inlet and outlet of the plenum. In acoustic analysis, tubes are often added to the inlet and discharge of the plenum to obtain planar waves at these locations. However in pressure pulsation calculation these tubes add additional resonance frequency and distort the pressure pulsation calculation. Better pressure pulsation agreement was obtain when only the 3D plenum geometry was used and the pressure outputs were the average pressure over an area.

After the basic geometry is determined a FEM harmonic analysis up to 3000Hz or higher is done to produce an impedance transfer functions as shown in Figure 1. The higher frequencies are used to analyze noise characteristic of the muffler or plenum.

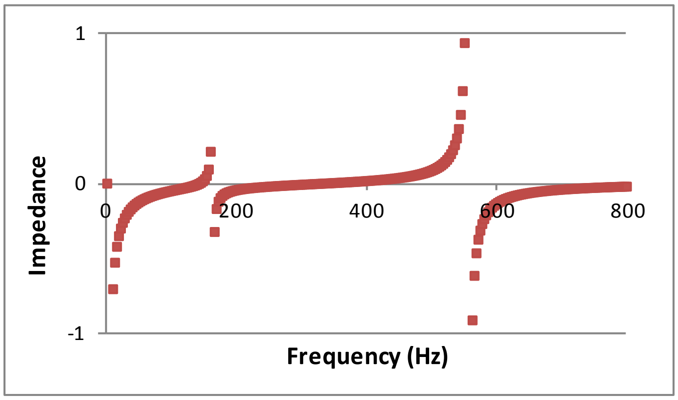

Figure 1. Typical impedance transfer function (one pole) from FEM harmonic analysis at the inlet due to flow through the inlet in a reciprocating compressor discharge muffler. There are two resonances occurring at 170 Hz and 550 Hz.

3. INCORPORATING IMPEDANCE FUNCTION INTO 1D COMPRESSOR SIMULATION PROGRAM

The simplicity of this method is the impedance transfer functions are normalized to FEM density and FEM sonic velocity. The frequency domain is normalized to only FEM sonic velocity and the impedance amplitude is normalized to FEM sonic velocity and FEM density, see Figure 2. This allows the FEM harmonic analysis to be solved only once to calculate the impedance parameters for all operating speeds, conditions or refrigerants. The normalized impedance transfer functions at each location are converted into a text file and then imported into the 1D compressor simulation program.

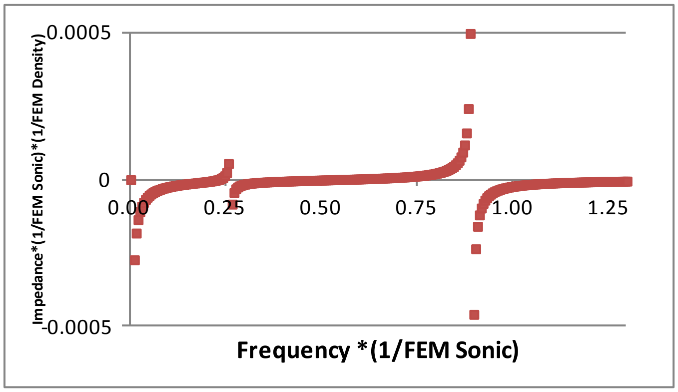

Figure 2. Normalized impedance transfer function from FEM harmonic analysis. Frequency domain is divided by FEM sonic velocity. Impedance amplitude is divided by FEM sonic velocity and FEM density.

During 1D compressor simulation, when the program calls for a four pole matrix or impedance matrix to calculate pulsation the program calls a subroutine to create this impedance matrix. The subroutine uses the density and sonic velocity from the 1D compressor simulation to create a new impedance transfer function at these conditions. It essentially multiplies the normalized frequency by the 1D simulation sonic velocity and the normalized impedance by 1D simulation density and sonic velocity to obtain the new impedance transfer function as shown in Figure 3.

The subroutine calculates the compressor operating speed harmonics and reduces the new impedance transfer function into an reduced impedance matrix at only the harmonics of the compressor speed (black diamonds below in Figure 3). This reduced impedance matrix can then be permuted into the four poles and used in the 1D compressor simulation program as describe in Zhou *et al*.(2001). However, it is easier to calculate pressure pulsations using the impedance matrix and not permute the variables into the four pole parameters.

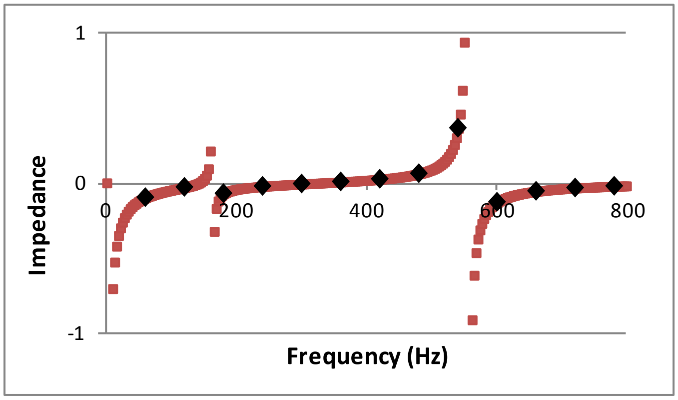

Figure 3. New impedance transfer function at 1D compressor simulation density and sonic velocity. Reduced impedance transfer matrix at compressor speed harmonics are represented as black diamonds.

4. DAMPING

The author first compared the basic 1D acoustic elements four pole parameters to FEM 3D calculated four pole parameters in Bilal *et al*.(2010) and had good agreement. The author also showed relatively good agreement between simulated pressure pulsation and CFD pressure pulsation results. However, when the mass flow frequency approached the plenum resonance the agreement between FEM simulated compressor pressure pulsation and measured pressure pulsation broke down. Experimental testing showed a phase shift, between the mass flow and pressure pulsation, occurred when the mass flow frequency approached the plenum resonance. According to multiple sources the four pole method did not have a reliable method for calculating pressure pulsations when the mass flow frequency approaches the resonances of the plenum. Through research and development the author developed a novel approach to include damping and phase shift into the impedance transfer function. These improvements and additional enhancements to the original hybrid method (Bilal *et al*. 2010) resulted in good agreement to the compressor suction and discharge pressure pulsations measurements and excellent agreement to CFD results. These agreements are shown later in this paper.

5. INPUT AND TRANSFER IMPEDANCE

The four pole method provides the pulsations calculations at the inlet and outlet of the plenum. However, it is very hard to locate a pressure transducer at these location and measure pressure. The further the pressure transducer is located from the inlet or outlet of the plenum the worst the agreement between simulated and measure pressure data. Singh and Soedel (1979) work provide input impedance and transfer impedance definitions. Input impedance is the pressure at an inlet or outlet divided by volume flow applied to at this same location. Transfer impedance is the pressure at a different location than the volume flow divided by the volume flow an inlet or outlet. However, for this paper the input impedance term was dropped and this impedance was also called transfer impedance.

Singh and Soedel (1979) showed how mass flow through one valve created pressure pulsations at a different valve in a multi-cylinder compressor due to the transfer impedance. This concept was adopted to determine the transfer impedance functions at pressure transducer location due to mass flow through an inlet or outlet. The mass flows through the pressure transducers are zero and are dropped from the mass (volume) flow matrix. The impedance transfer functions were expanded from a [2x2] matrix in four pole to a [NxM] matrix. Where N is the sum of inlets, outlets and pressure transducers locations of the plenum and M is the sum of inlets and outlets. The simulation requires the boundary conditions at the inlets and outlets be known as either mass flow or with a boundary condition.

6. RECIPROCATING COMPRESSOR SUCTION PLENUM PRESSURE PULSATION

Below in Figure 4, is 3D reciprocating compressor suction plenum models inside a hermetically sealed shell. The whole suction side system was modeled using FEM acoustic elements. Flow load was applied to the inlet surface of the shell compressor in the first FEM harmonic analysis run. Flow load in the second FEM harmonic analysis run was applied to the outlet (valve) surface. In acoustic analysis, tubes would normally be added to force planar waves at the inlet and outlet, however in pressure pulsation calculation the added tube will distort the impedance transfer function and have poor results. To handle non-planar waves at the inlet, outlet and pressure transducer the FEM pressure response is the average pressure over the surface area. The impedance transfer function is created by dividing the FEM average pressure at the four locations (inlet, outlet, PT 1, and PT 2) by the FEM flow load(inlet and outlet) at each frequency. This model creates 8 impedance transfer function or [4x2] matrix functions used in the 1D compressor simulation program to calculate pulsations.

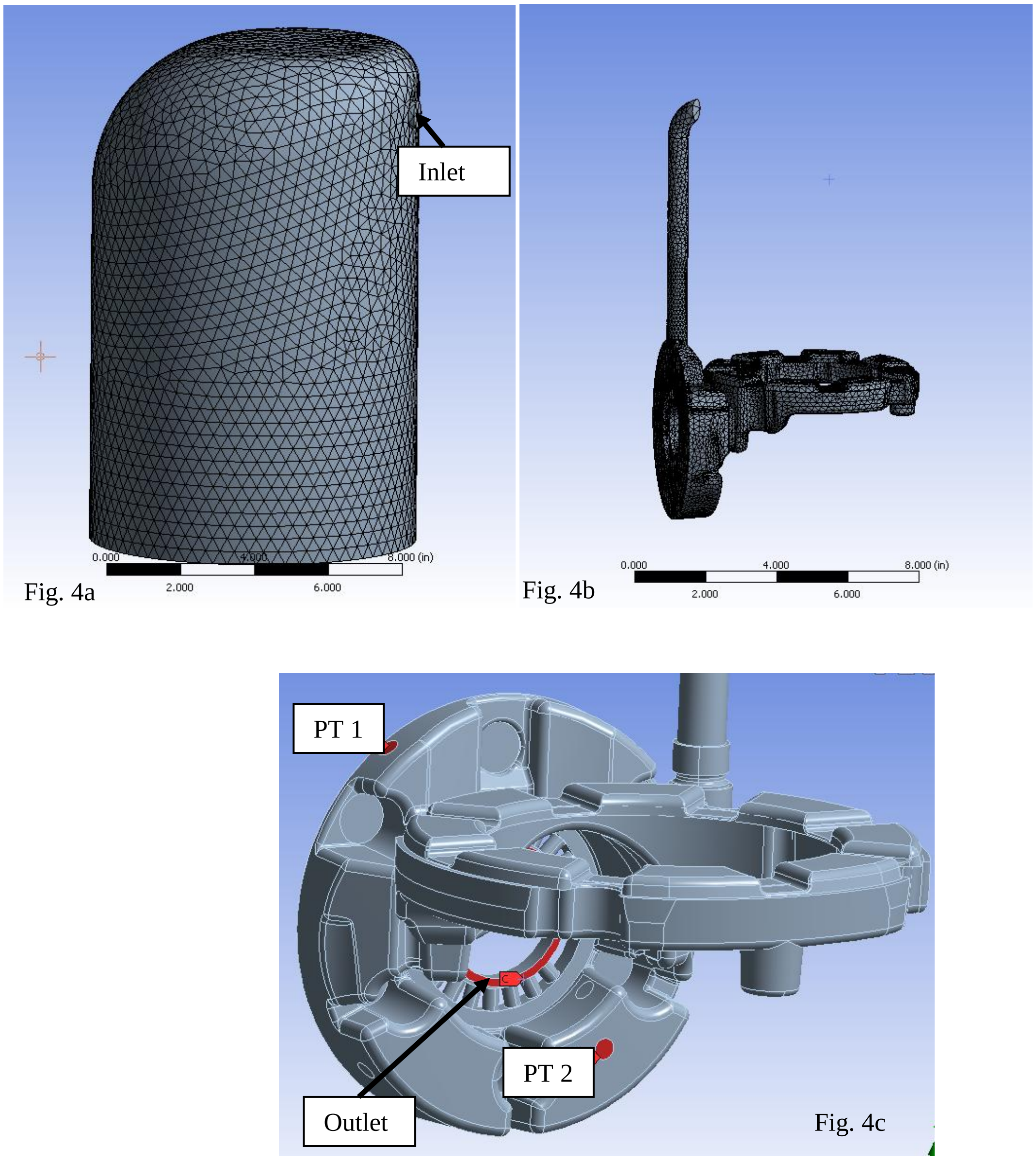

Figure 4. a) FEM model of the reciprocation compressor shell. b) FEM model of the intake plenum inside the compressor shell model. c) 3D CAD model of the intake system to show locations of pressure transducers (PT 1 and PT 2) and outlet of plenum(valve location).

The figures on the left side of Figure 5a-j compares 1D compressor simulated suction pressure pulsations without damping to suction pressure pulsation measured in Figure 4. The vertical figures are at different compressor speeds as the compressor fundamental speed passes through suction plenum resonance. The figures on the right side of Figure 5a-j have the corresponding speed as the left side figures but use damping and phase shift applied to the impedance transfer function. When damping and phase shift are applied to the impedance transfer function good agreement between simulated pressure pulsation and measured pressure is obtained. The high frequency in pulsation after the valve is open is due to resonance inside the cylinder. Figure 5i and Figure 5j has matched a 4^{th} order compressor speed with a resonance of the plenum; the “without” damping and phase shift simulation pressure pulsation become extremely large while the “with” simulation is in good agreement with the measured pressure.

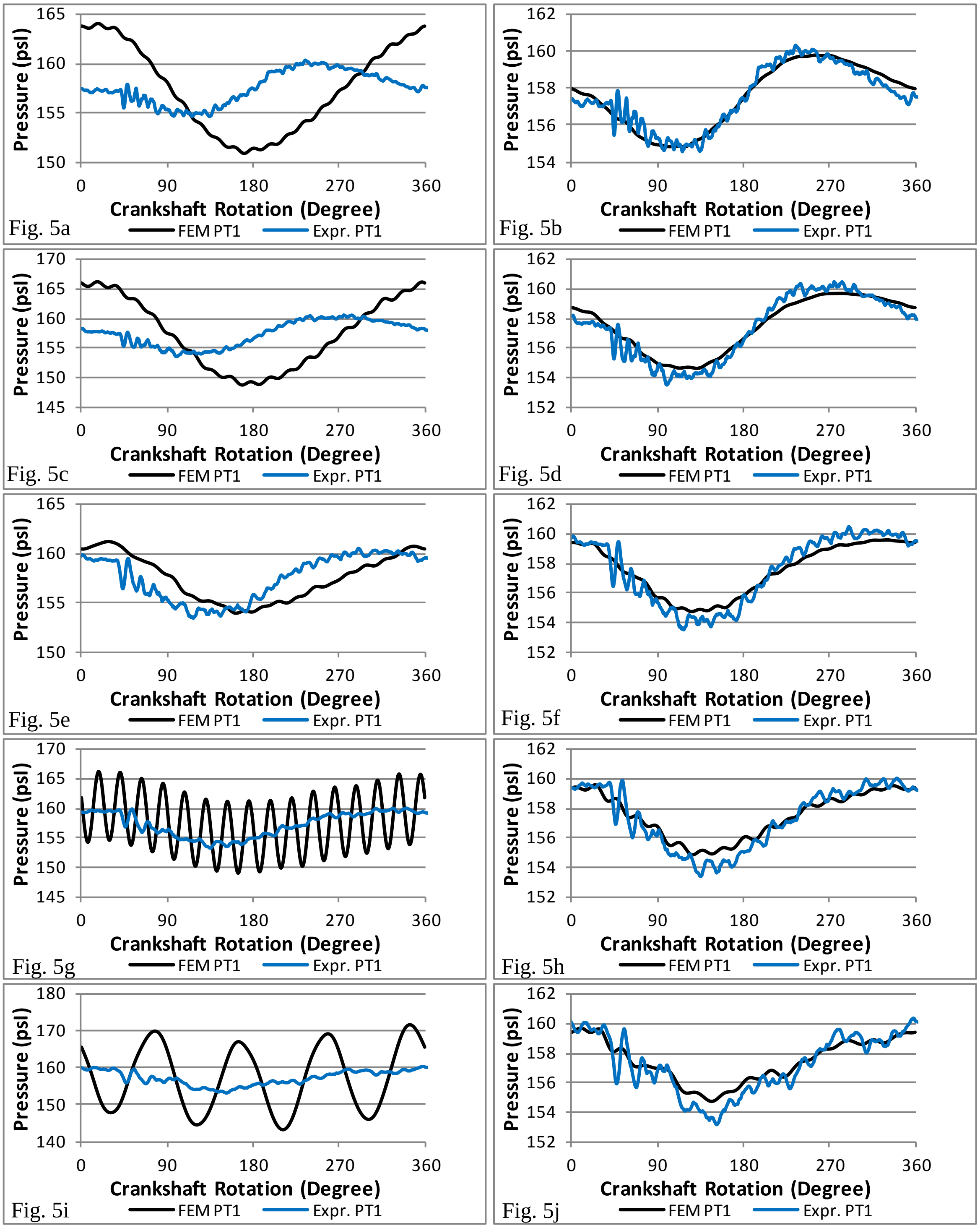

Figure 5a-j. Reciprocating compressor suction pressure pulsations at different operating speeds arranged vertically as the compressor speed passes through resonance of the suction plenum. Left side figure is without damping. Right side figure is with damping and phase shift. Blue line is measured pressure at pressure transducer 1 in suction plenum of reciprocating compressor. Black line is simulated pressure pulsation from 1D code using FEM impedance transfer function. Adding damping and phase shift to FEM impedance transfer function results in good agreement with measured pressure.

7. RECIPROCATING COMPRESSOR DISCHARGE PLENUM PRESSURE PULSATION

Below in Figure 6 is a photo and CAD 3D model of a reciprocating compressor discharge muffler. Two pressure transducers were added to the muffler at locations C (PT 1) and D (PT 2). Figures 7a and 7b, compares 1D compressor simulated pressure pulsations with damping and phase shift to measured pressure pulsation in a test compressor at two different speeds. Both speeds excite the same high order resonance inside the compressor muffler. The reduced impedance transfer matrix in Figure 3 was used to calculate the pulsation in Figure 7b. The ninth harmonic from Figure 3 matches the measured pressure pulsation harmonic frequency. The simulated pressure pulsations are in good agreement with the measured test data at both compressor speeds.

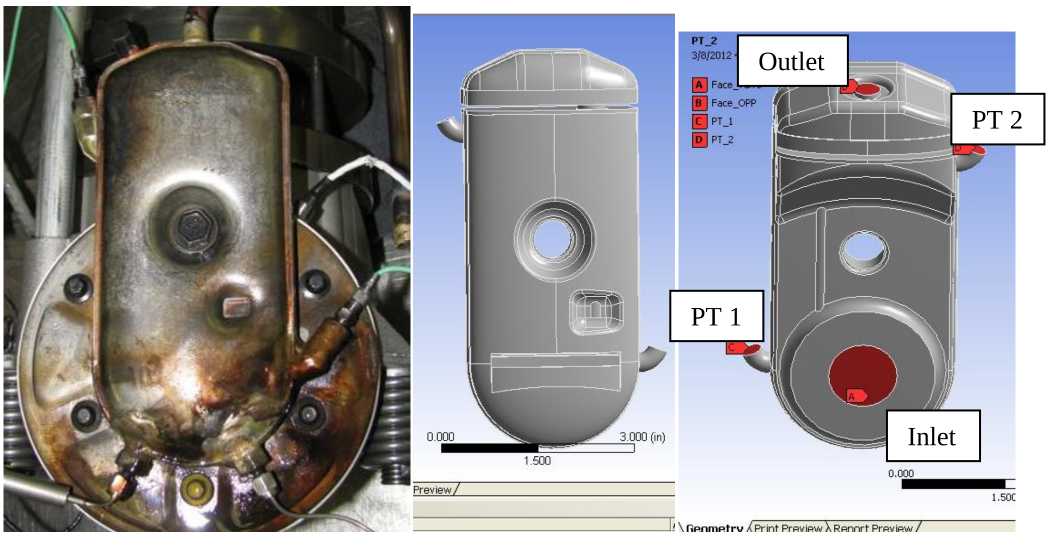

Fig. 6a Fig. 6b Fig. 6c

Figure 6. a)Photo of reciprocating compressor discharge muffler and pressure transducer locations. b-c) CAD 3D model of reciprocating compressor discharge muffler and location of inlet, outlet, and pressure transducers (PT 1 and PT2).

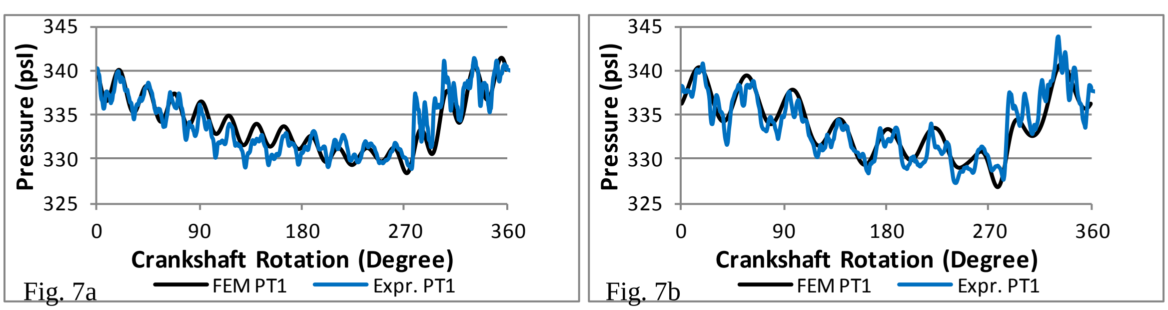

Figure 7. Measured (blue) and simulated (black) pressure pulsation at PT 1 inside reciprocating compressor discharge muffler at two different compressor speeds.

8. SIMPLE TWO CYLINDER SUCTION PLENUM.

The below CAD, Figure 8, was drawn to represent a simplified suction system of a two cylinder reciprocating compressor. This model was first analyzed in the paper by Bilal *et al.*(2010). Some questions arose during the presentation to why the CFD did not match the 1D basic acoustic or the hybrid method pulsations. The simple answer is at the time that paper was published the hybrid method did not use the improvements of damping and phase shifts in calculating pressure pulsation. When these improvements were included into the hybrid method the simulation pulsation matched the CFD results with excellent agreement, see Figures 9-11.

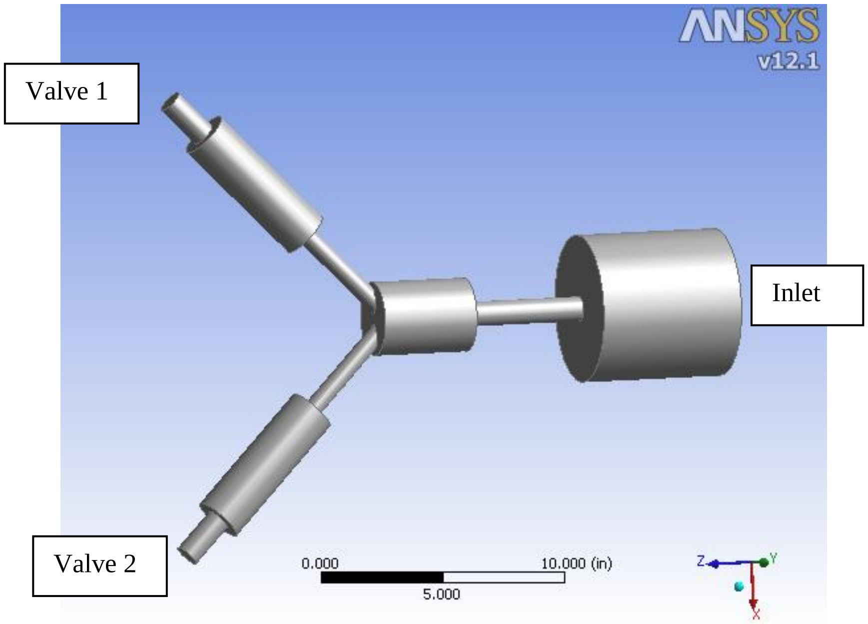

Figure 8. 3D CAD model of simple two cylinder suction system.

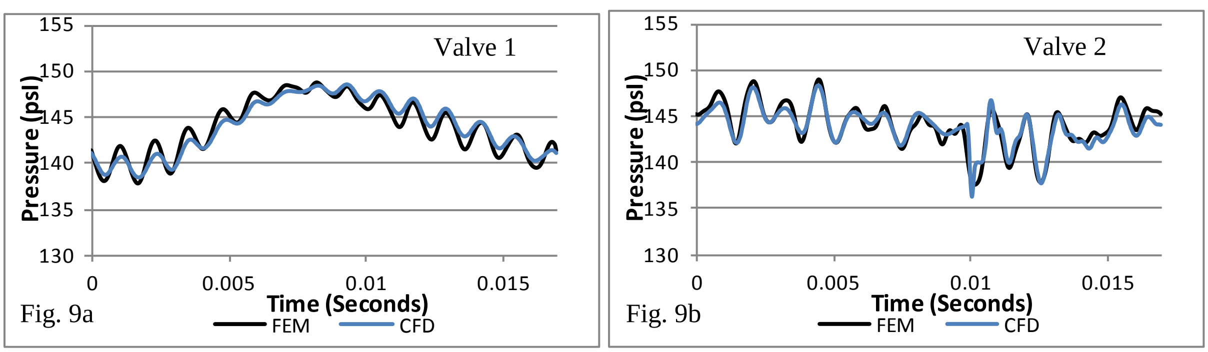

Figure 9. CFD (Blue) and 1D simulated (black) pressure pulsations at each valve with suction flow only through valve 2.

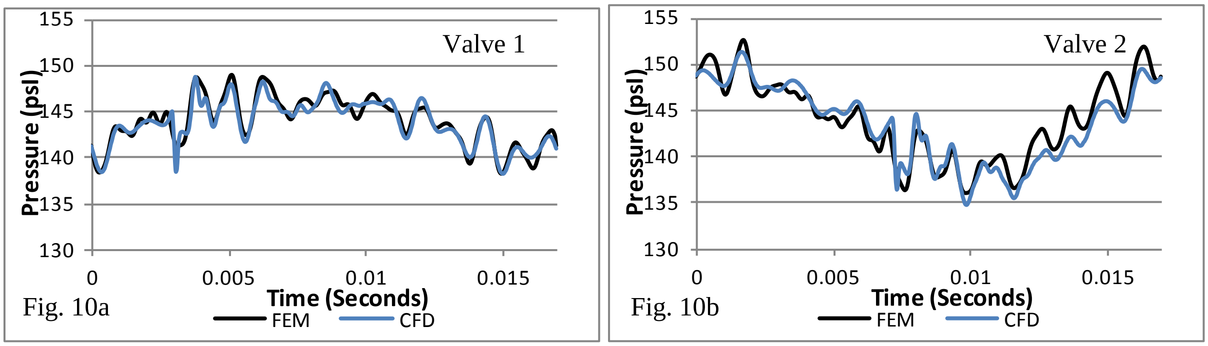

Figure 10. CFD (Blue) and 1D simulated (black) pressure pulsations at each valve with Valve 1 flow leading Valve 2 flow by 90 crankshaft degrees.

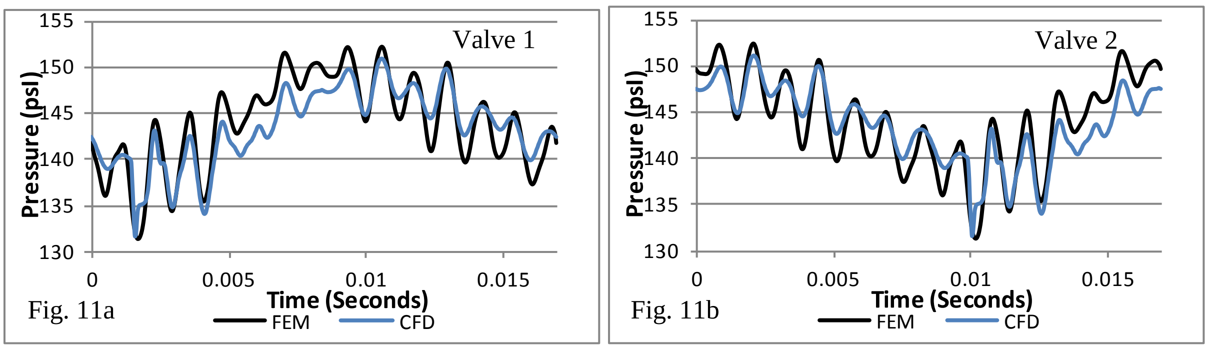

Figure 11. CFD (Blue) and 1D simulated (black) pressure pulsations at each valve with Valve 1 flow leading Valve 2 flow by 180 crankshaft degrees.

9. CONCLUSIONS

This paper shows good agreement between FEM impedance transfer function simulated suction pressure pulsations and the measured compressor suction pressure pulsations as shown in figure 5. As the speed of the compressor passes through renounces the simulated suction pressure pulsations are in good agreement with the phase shift in measured pressure pulsation. Good agreement is shown in figure 7 between the simulated compressor discharge pressure pulsations and measured compressor discharge pressure pulsations at the two different speeds. Finally, excellent agreement is shown in figures 9-11 between the compressor simulation pressure pulsation and CFD analysis. These agreements are the result of applying an improved damping and phase shift technique to obtain the FEM impedance transfer functions. This method allows complex 3D plenums to be easily integrated into a 1D compressor simulation program to calculate pressure pulsation. Because the impedance transfer functions can be normalized to FEM density and FEM sonic velocity only one density and sonic velocity condition needs to be analyzed by FEM harmonic analysis. The impedance transfer functions are also independent of mass flow, compressor speed, valve dynamics, sonic velocity, refrigerant density, refrigerant type, compressor type, bore size and stroke size. This allows for only one set of normalized impedance transfer functions per plenum are used in the 1D compressor simulation program to simulate pressure pulsations for any compressor operating condition and operating speeds. The FEM harmonic analysis results and impedance transfer functions show which frequency the pulsations will be low or high and allow the design engineer to redesign the plenum geometry to take advantage of this knowledge. This method allows a design engineer to design the plenum to enhance or reduce pulsations to improve compressor efficiencies. An additional benefit from the impedance transfer functions allows the design engineer to evaluate the acoustic noise performance of the muffler or plenum.

REFERENCES

Bilal, N., Adams, D., Novak, K., Sauls, J., 2010, A Hybrid Approach of Calculating Gas Pulsations in the Suction Manifold of a Reciprocating Compressor; *Proceedings of the 2010 International Engineering Conference at Purdue, Purdue University*; *July, 2010.*

Sauls, J., Novak, K., Incorporating 3D Suction and Discharge Plenum Geometry into a 1D Compressor Simulation Code to Calculate Compressor Pulsations; *Proceedings of the 2012 International Engineering Conference at Purdue, Purdue University*; *July, 2012.*

Singh, R., Soedel, W., 1979, Mathematical Modeling of Multicylinder Compressor Discharge System Interactions, Journal of Sound and Vibration, vol. 63, no. 1: p. 125-143.

Wu, T. W., Zhang, P., 1998, Boundary Element Analysis of Mufflers with an Improved Methods for Deriving the Four Pole Parameters, *Journal of Sound and Vibration,* vol*. 217, no. 4: p. 767-779.*

Zhou, W., Kim, J., Soedel, W., 2001, New Iterative Scheme in Computer Simulation of Positive Displacement Compressors Considering the Effects of Gas Pulsations, *Transactions of the ASME*, Vol*. 123, June 2001: p. 282-288.*