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Design Optimization of the Suction Manifold of a Reciprocating Compressor Using Sensitivity Analysis

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ABSTRACT

A new method for the design of the suction manifold of a reciprocating compressor using sensitivity and uncertainty methods was used. The objective was to pick the optimal values of the compressor suction manifold to minimize gas pulsations. The advantage of the method is that the input parameters do not have fixed values but a range is provided. Similarly, the output is specified in terms of a probability density function. Another advantage of this method is that we can set our limit on the maximum values of the gas pulsation that are permissible and then vary the input parameters so that all the gas pulsations are within the acceptable limits. This method also provides a way to compare gas pulsation level at different cylinder locations and how variations in an input parameter affect the gas pulsations at different locations.

1. INTRODUCTION

The main objective of doing uncertainty and sensitivity analysis is to provide the designer important insight and feedback about the performance and behavior of a simulation model. The focus of this paper is on using this information to develop a methodology to design a suction manifold of a reciprocating compressor for minimizing gas pulsation in the suction manifold. In particular, this method uses a range of values for each input parameter instead of a fixed value, and the output is expressed in the form of a probability distribution rather than a number. For example, say the manifold radius lies between 45 and 55 mm, the depth lies between 15 and 30 mm, and width lies between 10 and 16 mm. Using the design procedure outlined in next section, it would be possible to know ahead of time the cylinders in which the gas pulsations are occurring and to what extent. Such information can be extremely useful in reducing the prototype cost by knowing in advance how, by changing a certain parameter, the gas pulsation could be reduced. As mentioned above, a unique value of the parameter is not provided but a range of the input parameters is provided and the output is also not a single number but a probability distribution. In real world situations, there is rarely a case when precise values of the input parameters are known, rather there is always a range within which the parameter values lies. The mathematical model that is used in this simulation was developed by Park (Park, 2004) to calculate gas pulsations in the suction manifold of a reciprocating compressor. A brief description of the model is provided in the next section. After the model was validated for a nominal parameter set, uncertainty and sensitivity analysis was performed on the model using various local and global methods. These studies are detailed in (Bilal, 2011) and they determined the sensitivity of the gas pulsation in the compressor suction manifold to changes in the design parameters. The design parameters which affected gas pulsations the most, the critical frequencies, and the critical parameters that result in maximum gas pulsation were identified. The aim of this paper is to present a new methodology based on this previous work to design a suction manifold for minimizing gas pulsation in the suction manifold at various locations.

2. BACKGROUND INFORMATION

This research is performed using a detailed multi-cylinder automotive compressor model developed by Park (Park, 2004), which focused on modeling and simulating pressure pulsations in the suction manifold of a reciprocating compressor. The actual compressor, the suction manifold, and simplified geometric model are shown below in Figure 1.

(a) (b) (c)

Figure 1: (a) A multi-cylinder reciprocating compressor and; (b) the suction manifold of the compressor with suction valves marked; (c) simplified geometric representation of the suction manifold, where r, b, and h_a respectively represent radius, depth and width of the suction manifold.

This model calculates the cylinder pressure and temperatures during a cycle, predicts the valve dynamic responses, and calculates mass flow rate through each of the suction ports. Mass flow rate was used as an exciting function in the acoustic model to calculate the gas pulsation in the suction manifold. The schematic of the basic simulation model is shown in Figure 2 and details can be found in Park (Park, 2004) and (Park & et al, 2008).

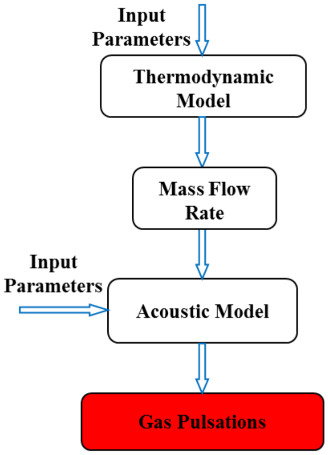


Figure 2: The basic compressor simulation model

3. SUMMARY OF THE SENSITIVITY ANALYSIS OF THE COMPRESSOR SIMULATION MODEL

Sobol's method of sensitivity analysis was applied to a compressor simulation model, the details of which can be found in (Bilal, 2011). The details of different uncertainty and sensitivity analysis methods and approaches that were applied to compressor simulation model are in (Bilal, 2011). Here a very brief explanation of the simulation procedure to implement Sobol's method of sensitivity analysis, based on decomposition of variance, is presented to provide context for the current design optimization study.

It is also important to mention that the given compressor has 7 cylinders; however, only 6 cylinders are shown in all the plots. Cylinder five is not shown because the experimental data for cylinder location 5 was not available to compare with the simulation results. However, the effects of cylinder 5 were included in calculating gas pulsations in the suction manifold of the compressor.

3.1 Sobol's Method Applied to a Compressor Model.

Sobol's method, a global sensitivity analysis method, was applied to the compressor simulation model. The objective was to determine the sensitivity of gas pulsations to design parameters of the suction manifold. The actual suction manifold is shown in Figure 1. The method was implemented by following a series of steps as outlined below:

- The parameters and their ranges of variation were defined as shown in Table 1.
- A probability distribution to sample the variables was defined. In this case, a uniform distribution was chosen to generate the input vector.
- Simulations were run for 295 iterations.
- The sensitivities of three input parameters as described in Table 1 were determined using Sobol's method.

Table 1: Numerical values of the variables used in simulation

Variables	Mean (mm)	Minimum Value (mm)	Maximum Value (mm)
Manifold radius, ***r***	50	30	70
Manifold depth, ***b***	27	20	40
Manifold width, ***ha***	14	8	20

These parameter values were chosen so that some of the geometric constraints of the manifold were still satisfied, and at the same time, the system was sufficiently perturbed in order to observe the effects of sensitivity analysis. The operating conditions for the thermodynamic model were chosen to be a speed of 2000 rpm and a mass flow capacity of 90 kg/hr. The thermodynamic model was run at the nominal values and no variables were changed in that model to calculate the mass flow rate, which is the excitation function for the acoustic model. The output of the thermodynamic model was used in conjunction with the acoustic model to calculate the pressure pulsation in the suction manifold.

First order effects and total effects of the gas pulsation due to changes in the suction manifold radius, width and depth were calculated. It may be helpful to mention that first order sensitivity indices indicate the impact of the individual parameters on the model output, while the total effects indices characterize the influence that an individual parameter may have in any combination of other parameters on the model output (Bilal, 2011). It was shown that the suction manifold pressure response was most sensitive to changes in manifold radius, followed by manifold width and depth. Figure 3 shows the first order effects of parameter variation on the gas pulsation in the suction manifold at valve location 6 in the frequency range of 0-1200 Hz. Most of the compressor noise related problems are in the low frequency range. Figure 4 shows the Total effect of the gas pulsation due changes in the suction manifold radius, width and depth. The total effect of manifold radius r describes the effects of the interactions between changes in r with changes in the manifold depth b and width ha. For a linear system, the total effect should add up to unity. Figure 4 shows that parameter r has much more impact across the entire frequency range. Upon closer observation, the value of r at certain frequencies is more than one (red line in Figure 4), which indicates that there are nonlinear interactions taking place by changing the parameter r. Also, the total sensitivity coefficients are much higher indicating that there is a significant nonlinear interaction taking place with variations in r.

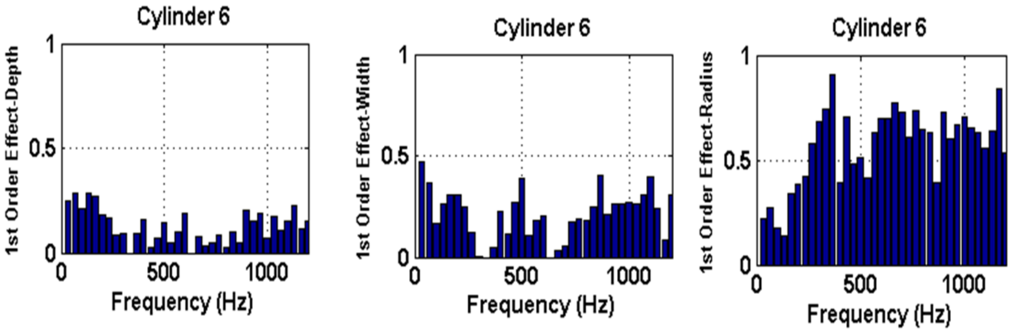


Figure 3: First order indices of manifold depth, width and radius, using Sobol's method.

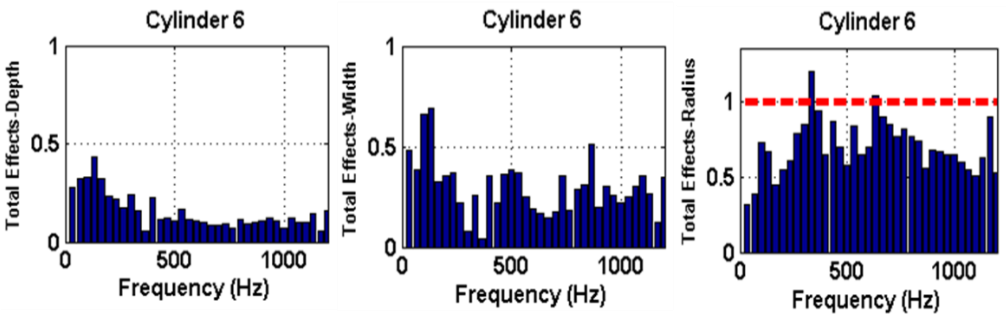


Figure 4: Total effect indices manifold depth, width and radius, using Sobol's method.

The above analysis was performed to do determine the sensitivities of the three design parameters of the suction manifold and their relative sensitivities. In the next section, more specific information about these parameters would be extracted to aid design optimization of the suction manifold.

4. STEPS FOR DESIGN OPTIMIZATION—AN ITERATIVE SCHEME

This section discusses the overall approach for the design optimization of the compressor suction. While all the detail and are given in (Bilal, 2011), some of the important details and concepts that are used in the simulation are provided here for better understanding.

Total Manifold Energy: Total manifold energy is the total energy in the suction manifold due to gas pulsations. The total energy is calculated by summing the pulsation energy from each cylinder location. The purpose of doing manifold energy analysis was to generate a set of parameters that results in minimizing gas pulsation in the suction manifold. These set of parameter are used as a starting in the design optimization studies. The details of these could be found in (Bilal, 2011).

Critical Frequencies: Critical frequencies are those frequencies at which maximum gas pulsation occur within the suction manifold. When performing sensitivity analysis, it is observed that maximum pulsations usually occur at a few particular frequencies of the manifold pressures response. When designing a suction manifold we want to observe the pressure response at those critical frequencies. The first set of natural frequencies (acoustical) was determined to be at 433 Hz and 500 Hz. Sensitivity analysis of the manifold also showed that 666 Hz and 733 Hz were also critical frequencies as gas pulsations were observed to be maximum at these two natural frequencies. In designing the suction manifold it is best to observe the behavior of gas pulsations at all the critical frequencies. The details on how to identify those frequencies can be found in (Bilal, 2011). Here 433 Hz frequency is chosen to outline the suction manifold design procedure. Similar analysis could be extended to other critical frequencies without any change in the design procedure.

Pressure Maps: Pressure maps provide an overall picture of how pulsation energy is distributed within the cylinders for each design iteration. Pressure maps provide a quick visualization of the locations and frequency at which maximum pressure pulsation energy occur as design parameters are varied (Bilal, 2011). These also give the designer an overview of how maximum gas pulsation jump between frequencies as parameters are varied and the direction in which a parameter should be changed to obtained desired level of pulsations.

The total manifold energy is used to select the parameter for the initial iteration. Selecting the parameter set with the lowest total manifold energy is a good starting point because low manifold energy correlates to low pulsations. Next, the critical frequencies are identified. Pressure maps are used to provide both a qualitative picture of how the pulsation energy jumps between critical frequencies as the parameters are varied and also the limits on pressure pulsation (Bilal, 2011). All the above mentioned steps provide both quantitative and qualitative insight about how parameter variations affect gas pulsations in the suction manifold. The above mentioned concepts were used in the design optimization procedure and are schematically presented in Figure 5.

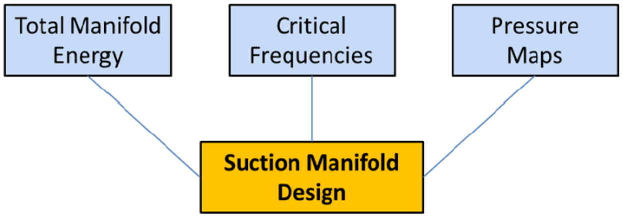


Figure 5: Design optimization procedure for a suction manifold using uncertainty and sensitivity analysis

4.1 Procedure for Design Optimization Studies:

The procedure for design optimization is based on the feedback from sensitivity analysis studies and other inputs (like pressure maps and total pulsation energy) to optimize the manifold design. In the first step, parameter data was generated to perform the Sobol method of sensitivity analysis as described in section 3.1. This data is also used to calculate total manifold energy, which results in choosing the set of parameters that yield the minimum gas pulsations, and are used as a starting point in the design optimization study. The amplitudes of gas pulsation in each iteration are evaluated and the probability of it lying within the prescribed limits is evaluated and compared at each cylinder location. Based on the results of this analysis a new set of parameters is generated and the same process is repeated until desired results are achieved. This design process is illustrated with the flow chart in Figure 6. Some sample design calculations are shown in the next section.

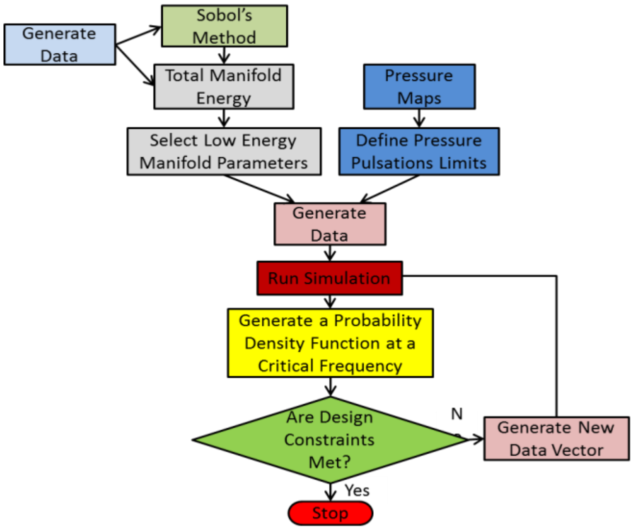


Figure 6: Suction manifold design procedure

4.2 Procedure for generating a histogram

In performing design optimization studies, all parameter were varied simultaneously within the parameter space of interest, and gas pulsations in the suction manifold were calculated. Since it is a multicylinder compressor, at each cylinder location we get a frequency pressure response for the frequency range of interest as shown in Figure 7. As mentioned earlier, we are interested in looking at minimizing the pressure response at a critical frequency. In this example, 433 Hz was identified as a critical frequency. When a further design constraint is applied on the simulation parameter, the result is a small set of simulations that meet those design constraints. The results of those pressures pulsations at a particular cylinder location and critical frequency (433 Hz in this case) are plotted as a histogram which is then approximated by a probability density function, as shown in Figure 8.

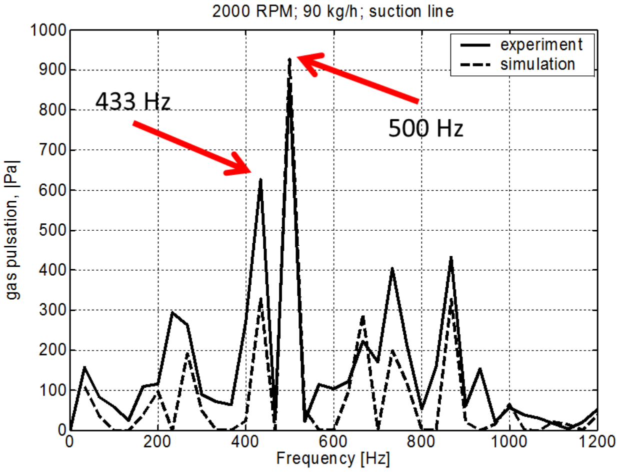


Figure 7: A typical pressure response in the suction manifold compared with the experimental data at 90 Kg/h and 2000 rpm. The first two critical frequencies, 433 Hz and 500 Hz are shown by red arrows.

The frequency count refers to the number times the gas pulsations of particular amplitude occur with the given set of design constraints. The next step involves calculating the probabilities that gas pulsations are within the given limits and the probabilities that gas pulsations are beyond the upper limit on gas pulsation. Finally, the mean and standard deviation for the gas pulsations that are within the given limit are calculated to explain how gas pulsations at any particular cylinder location are concentrated and how are they fluctuating.

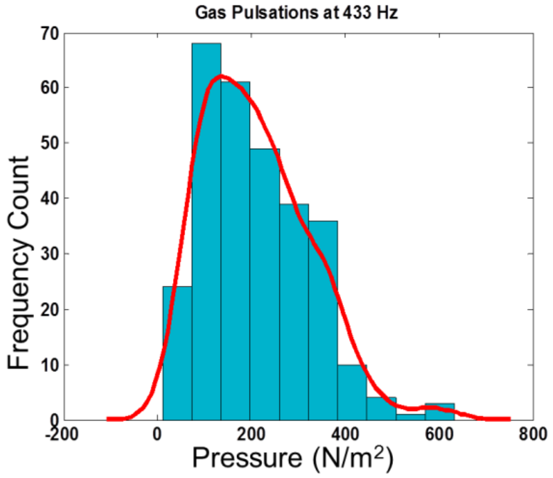


Figure 8: Histogram for gas pulsation in the suction manifold at 433 (Hz) for 2000 RPM and 90 Kg/hr (blue). The red-line indicates the approximation.

4.3 Some sample simulations

To illustrate the design simulation procedure, two iterations of the process are presented here. The iterative design procedure for the optimization of the suction manifold is repeated until acceptable design values are achieved. The parameters that are varied in the cases are shown in Table 2 and the parameter limits are shown in Table 3.

Note: The critical frequency in all iteration is chosen to be 433 Hz.

Table 2: List of design parameters that are varied

Parameter	Denoted by
Manifold radius	r
Manifold depth	b
Manifold width	ha

4.4 Design Iteration Number 1

Table 3: The limits on the parameters chosen for first iteration and the pressure pulsation.
Critical Frequency is 433 Hz.

Parameters	r (mm)	b (mm)	ha (mm)	Pulsations Limit (N/m^2)
Lower limit	45	20	10	200
Upper limit	55	30	16	500

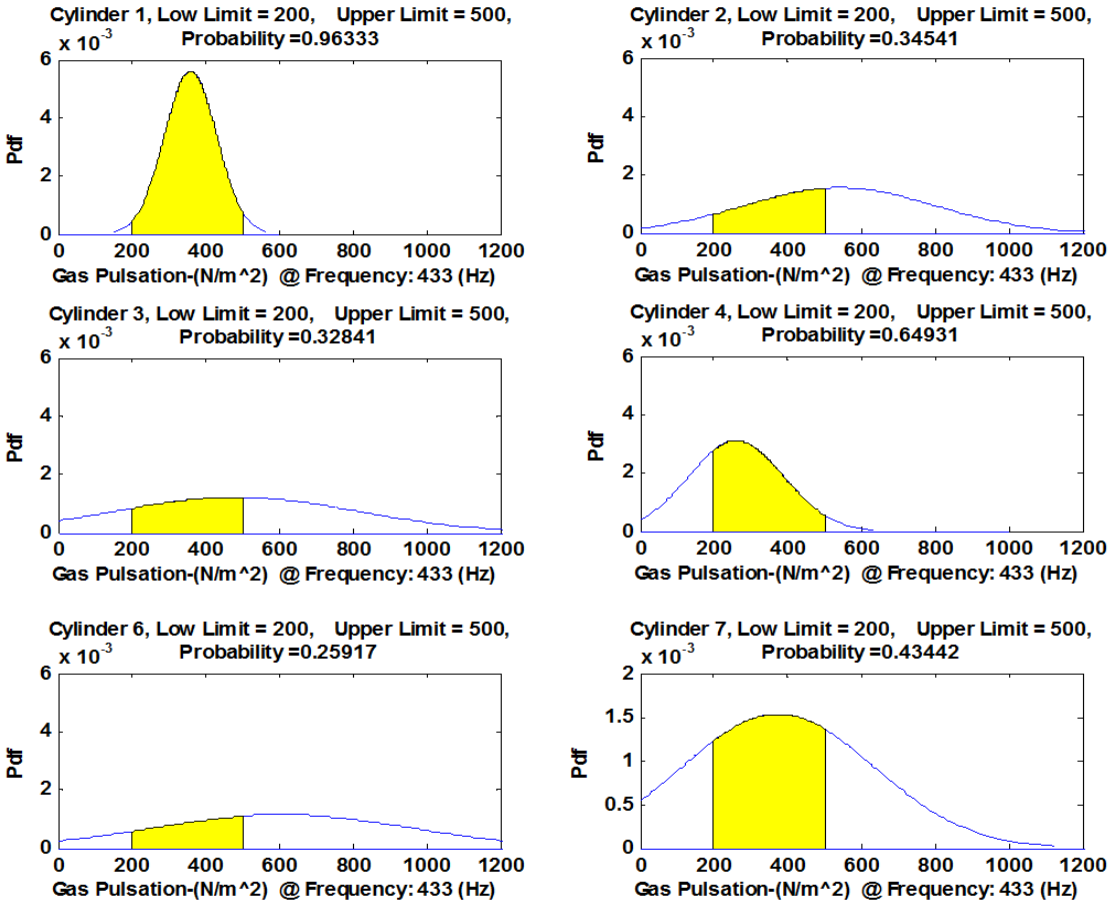
Figure 9 shows the probability density function for gas pulsations for the six cylinder locations at 433 Hz and Table 4 show the vital statistics that give a clear picture of how the gas pulsations are varying along different manifold positions. The yellow shaded section in Figure 9 and 10 shows the part of the pdf which are within the prescribed limits set for gas pulsations. It is also important to realize that the pdf will be higher when the gas pulsation are with in the prescribed limis and lower when the gas pulsations are outside the prescribed limits. A quick look at Table 4 shows all the cylinder locations and the gas pulsations at cylinder location 6 have the highest mean and standard deviation. It is important to note that these pulsations are generated by the same set of parameters for all locations, so the design parameter have to carefully selected so that pulsations at all locations are within acceptable limits.

Figure 9 shows that cylinder location 2 and cylinder location 6 are outside the premissible range. Moreover, the standard deviations for all location are also high. Therefore it is necessary that the gas pulsation be further reduced and evenly distributed by choosing a new set of parameters.

Table 4: Summary table for design iteration number 1

Cylinder No.	1	2	3	4	6	7
Mean	358.96	540.46	482.55	260.3	606.13	373.79
Std.	71.231	256.03	325.85	128.58	346.33	259.97
Prob.	0.9633	0.3454	0.3284	0.6493	0.2592	0.4344
Pu	0.0239	0.5628	0.4787	0.0311	0.6204	0.3137

- Here Std. denotes standard deviation, *P* denotes the probability and *Pu* the probability that pulsation are higher than the upper limit set for maximum pulsations.



Cylinder 1, Low Limit = 200, Upper Limit = 500, Probability =0.96333

Cylinder 2, Low Limit = 200, Upper Limit = 500, Probability =0.34541

Cylinder 3, Low Limit = 200, Upper Limit = 500, Probability =0.32841

Cylinder 4, Low Limit = 200, Upper Limit = 500, Probability =0.64931

Cylinder 6, Low Limit = 200, Upper Limit = 500, Probability =0.25917

Cylinder 7, Low Limit = 200, Upper Limit = 500, Probability =0.43442

Figure 9: Probability density function for parameter ranges: radius 45-55mm; depth 20-30 mm; width10-16mm, for specified pressure limits for each cylinder location.

4.5 Design Iteration Number 2

In this iteration, the value of ha upper limit has been increased from 16 to 24. Since gas pulsations at only two cylinder locations were outside the prescribed limit, a less sensitive parameter (ha) was varied in an effort to ellicit a small change in the output. If larger changes were necessary, a more sensitive parameter could be chosen to more drastically affect the gas pulsations.. The new limits on the parameters are shown in Table 5:

Table 5: **:** The limits on the parameters chosen for first iteration and the pressure pulsation. Critical Frequency is 433 Hz.

Parameters	r (mm)	b (mm)	ha (mm)	Pulsations Limit (N/m^2)
Lower limit	45	20	10	200
Upper limit	55	30	24	500

Figure 10 and Table 6 provide the pressure pulsation information for design iteration 2. In the above iteration the value of *ha* upper limit was increased from 16 to 24 mm. By making this change, it is seen that the overall pulsations are more balanced across all the manifold locations. It is also seen that the probability levels are more uniformly distributed at all cylinder locations. It is seen that except for cylinder location 6, gas pulsation at all other locations are well below the prescribed limit. Moreover, the standard deviation of the pulsations within the prescribed limits has also been reduced, which indicates less pressure fluctuations.

The design iteration process should be repeated in a similar fashion until all the constraints either have been fully met or as closely achieved as possible. Also for the same parameters it is also possible to examine different frequencies at the same time for a particular cylinder location. The main advantage of these plots is that they provide a quick snapshot of which particular location is generating more pulsations and how those pulsations concentrate at that particular location. Parameters can be adjusted to determine the best design solution for balancing the pulsations in the manifold. It also identifies what is the probability that the gas pulsations are higher than the given range.

Table 6: Summary table for design iteration number 2.

Cylinder No.	1	2	3	4	6	7
Mean	320.77	477.79	411.19	195.03	545.12	309.5
Std.	70.034	186.22	234.51	104.44	249	189.5
P	0.9524	0.4796	0.4636	0.4793	0.3452	0.5609
Pu	0.0052	0.4525	0.3525	0.0018	0.5719	0.1574

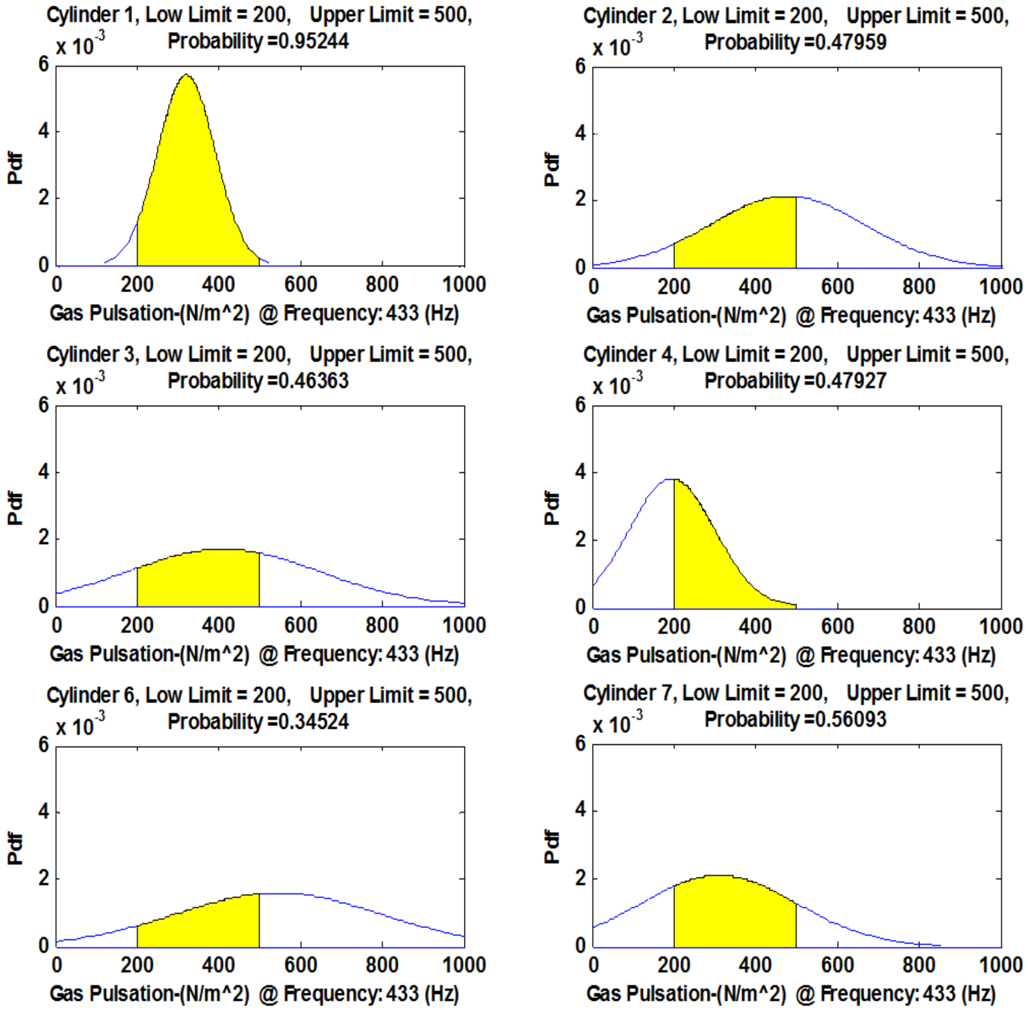


Figure 10: Probability density function for parameter ranges: radius 45-55 mm; depth 20-30 mm; width 10-24 mm, for specified pressure limits for each cylinder.

5. CONCLUSIONS

A new iterative method of designing the suction manifold of a reciprocating compressor using uncertainty and sensitivity analysis was developed. This new method can predict the response of the output in terms of a probability distribution. The same tool can be used to examine all the critical frequencies for all the cylinders. A precise or exact value for any parameter has not been specified but a bound or range on the input parameters was specified and the output was described in terms of a probability distribution. The desired pulsation limits were specified and the probability of having gas pulsation within that particular range was also specified. This tool would be helpful when designing a compressor, pump or similar equipment where the designer only has a rough idea of the design and geometric parameters and would be interested in looking at the general trend of how gas pulsations vary in different cylinder locations and also picking the set of design parameters that minimize them. It would help understand how variations in a parameter would affect the output response and how much design tolerances would be adequate.

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