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ABSTRACT

All compressor simulation models have uncertainties in model parameters and variability in operational parameters. The thermodynamic and noise performance of a multi-cylinder, automotive compressor suction process are investigated in this study. The main focus is on uncertainty and variability in compressor models to improve model accuracy and identify feasible design solutions that are robust to sources of variability. Uncertainty Analysis and Sensitivity Analysis tools are used to assess and quantify the effects of variability and uncertainty in compressor simulation models. Based on initial sensitivity analysis of a few model input parameters, it is shown that the output response is most sensitive to the valve model parameters. The valve model is the key factor in determining the mass flow rate that is subsequently used in determining gas pulsations in the suction manifold of a compressor. The compressor simulation model is used to identify the combination of input variables that produce the maximum and minimum levels of gas pulsations and also to select the design and operation parameters which result in the lowest levels.

1. INTRODUCTION

This research is focused on assessing the uncertainty and variability in compressor models to improve model accuracy and identify feasible design solutions. Both thermodynamic and noise performance of a compressor suction process are examined. In all compressor simulation models, there are uncertainties in model parameters and variability in operational parameters. The conventional approach to compressor simulation is to fix these parameters. In statistical analysis, the parameters are permitted to vary according to some probability density function. When groups of parameters are statistically sampled in simulations, a high mean of the output indicates the parameters have greater influence and a high standard deviation indicates a greater interaction among the different parameters. Uncertainties are present in the simulation model input parameters as well as the structure i.e., the terms of the model. In fact, different models are often used for different sets of operational parameters, for example, when the compressor speed, capacity, or both are varied. This research addresses this variability aspect of simulation models by using Uncertainty Analysis (UA) and Sensitivity Analysis (SA) (Saltelli, 2000a) to better understand and quantify sources of variation in the model in order to infer useful information about the prediction capabilities of the model when parameters validated by experiments are modified. The anticipated result is a methodology for determining key groups of parameters in compressor simulation models that control the simulation output uncertainty so that optimal and robust design solutions can be obtained. UA of a model aims to quantify the overall uncertainty in the model output by taking into account all uncertainties associated with the input variables and model parameters. SA aims to attribute the output uncertainty in quantifiable terms to the contribution by each input parameter.

2. BRIEF DESCRIPTION OF RESEARCH

This research consists of two main stages. In the first stage (Park, 2004a), a simulation model for multi-cylinder automotive compressor was developed. The main objective of that work was to utilize the simulation model to specify compressor design parameters that reduce the gas pulsation in the suction manifold. The complete compressor model consisted of sub models of compression cycles based on first law of thermodynamics, dynamics of the suction valve, and mass flow rate equations for the valve ports, all combined and solved simultaneously (Park, 2005). After demonstrating that the model predicted the experimentally measured thermodynamic processes and valve dynamics, the model was used to predict the gas pulsations in the suction manifold. In the second stage of this research, the objective is to use UA and SA tools (Saltelli, 2004) to assess and quantify the effects of variability and uncertainty in compressors simulation models. The goal is to develop predictive models with more accuracy and less uncertainty and to select compressor parameters to improve noise and vibration as well as refrigeration performance. The results of the previous research (Park, 2004) will serve as a foundation for this proposed work by providing analytical models, simulation results, and experimental data. This research explores those aspects of the compressor that explain why certain combinations of parameter changes have more effect on the compressor performance. Given the uncertainty and variability in the model and operational parameters, this research quantifies and helps to interpret uncertainties in the output parameters. Some initial simulations have been run using sampling techniques on a few input parameters. In this work, the distribution of output compressor gas pulsations was analyzed.

3. PRINCIPAL APPROACH: PROBABILISTIC-BASED MODELING OF INPUTS

The main reason for using probabilistic methods of sensitivity analysis as opposed to the one-at-a-time (OAT) method (Iman, 1986) is that the probabilistic methods allow one to identify interactions among different input variables (Iman, 1981). The compressor model used in this research is highly nonlinear, modular and has many variables that make it very difficult to use the typical OAT. The results of OAT are mostly valid if the model is linear. In that case, varying one variable at a time with the other variable fixed, highlights the relative contribution of each input variable. However, gas pulsations in multi-cylinder compressor models in the suction and discharge manifold are quite complex because of the interactions between different valves. The OAT approach can only provide conditional information, which at times can also be quite misleading. By using a probabilistic approach, (Iman, 1986) these pitfalls can be avoided by using sampling techniques like Latin Hypercube Sampling (LHS) (Wyss, 1998), which not only spans the entire input space but also varies all the variables simultaneously. This approach makes LHS quite efficient and provides meaningful insight into the output behavior of the response.

4. OBJECTIVES

UA and SA tools are used to analyze gas pulsations in the compressor and the overall behavior of the mathematical models to achieve the following:

- To verify the robustness of the simulation model. Is it too sensitive to parameters like mass flow rate, rotations speed, valve stiffness, etc? Can it generalize over a wide range of operating conditions?
- To find shortcomings in all compressor models identified by UA and SA.
- To make model simplifications, i.e., using UA and SA to construct a simple model with a few variables. The current model requires a long time to simulate.
- To improve and enhance the overall compressor design by analyzing thermodynamic and acoustic models at the sub component level and also globally.
- To find the best set of parameters that provide the optimal solution, and also to find what the different design scenarios are when a certain parameter is changed and other variables are fixed i.e., to identify how the remaining variables cause changes in response.
- To identify and document the difficulties associated with this type of study of compressor models and to find what input from experimentalist is needed to perform better SA.
- To use compressor simulation models to develop a general methodology for UA and SA applicable to a wide and diverse variety of problems.

5. BENEFITS

Some of the benefits to be achieved from the above approach are:

- Using UA and SA to direct research priorities to enhance the overall compressor design by focusing on the factors that dominate the uncertainty in compressor models.
- Reducing the costs associated with prototype testing.
- Finding faster ways to compare different design scenarios in compressors with critical component like the suction valve, and checking different design scenarios.
- Optimizing the different parameters involved in the compressor design resulting in lower gas pulsations.
- Applying UA and SA to detect the causes of fluctuations in the gas pulsations and also the nonlinear relationship between input and output, which normally goes undetected in the usual analysis.

6. THE GENERAL APPROACH

The general approach taken in doing UA and SA (Satelli, 2000a) is to study the effects of changing some variable on a global level using the probabilistic approach. The brief details of this approach are outlined below:

- Select variables for analysis. Criteria: Subjective information about the model, analysis of scatter plots, or expert opinion.
- Select range of input variables and model parameters.
- Assign a subjective probability distribution for each of the uncertain variables. If no information is available, uniform distribution is assigned or in the case where the input range spans several orders of magnitude, a lognormal distribution can be used.
- Generate data from these distributions. Monte Carlo Simulation (MCS) or Latin Hypercube Sampling (LHS) are used.
- Account for correlations among parameters, if correlations are found to exist.
- Propagate the uncertainties through the model.
- Analyze simulation results by studying the output distribution.
- Rank parameters contributing most to uncertainty using some SA technique.
- Interpret uncertainty in the output response by analyzing the mean, standard deviation, and correlation coefficient, etc. to gain insight into how the model is responding.
- Obtain additional data (if needed) for the most important model parameters and repeat the above steps.

7. AREAS OF RESEARCH FOCUS

The first phase of the study identifies the key areas on which to focus. The main mathematical models that required further investigation are the manifold acoustical model, the reed valve model, the associated thermodynamic models, and the variations associated with suction/discharge lines. The principal focus is on the gas pulsations in the suction manifold and the effects of valve dynamics, which are linked together through a single variable, the mass flow rate. Other critical factors identified are crank speed (rpm), natural frequency, temperature, speed of sound, the nature and type of fluid forces on the valve, the time step, effect of the stopper stiffness, and the effect of the dissipation factor. The valve dynamics is an important factor in the overall simulation involving the stiffness and impact of the valve, height between the seats, and clearance volume and stroke of the piston.

8. MODEL SPECIFIC DETAILS AND IMPLEMENTATION

The complete computer simulation model consists of two sub computer models (Park, 2004), the first consisting of the thermodynamics and valve dynamics of the compressor and the second consisting of the acoustic model, used for calculating the gas pulsations. The first model among other things calculates the mass flow rate in the compressor, and this information serves as the input to the second model, which calculates the gas pulsations in the suction manifold. The complete simulation flow chart is explained in Fig. 1.

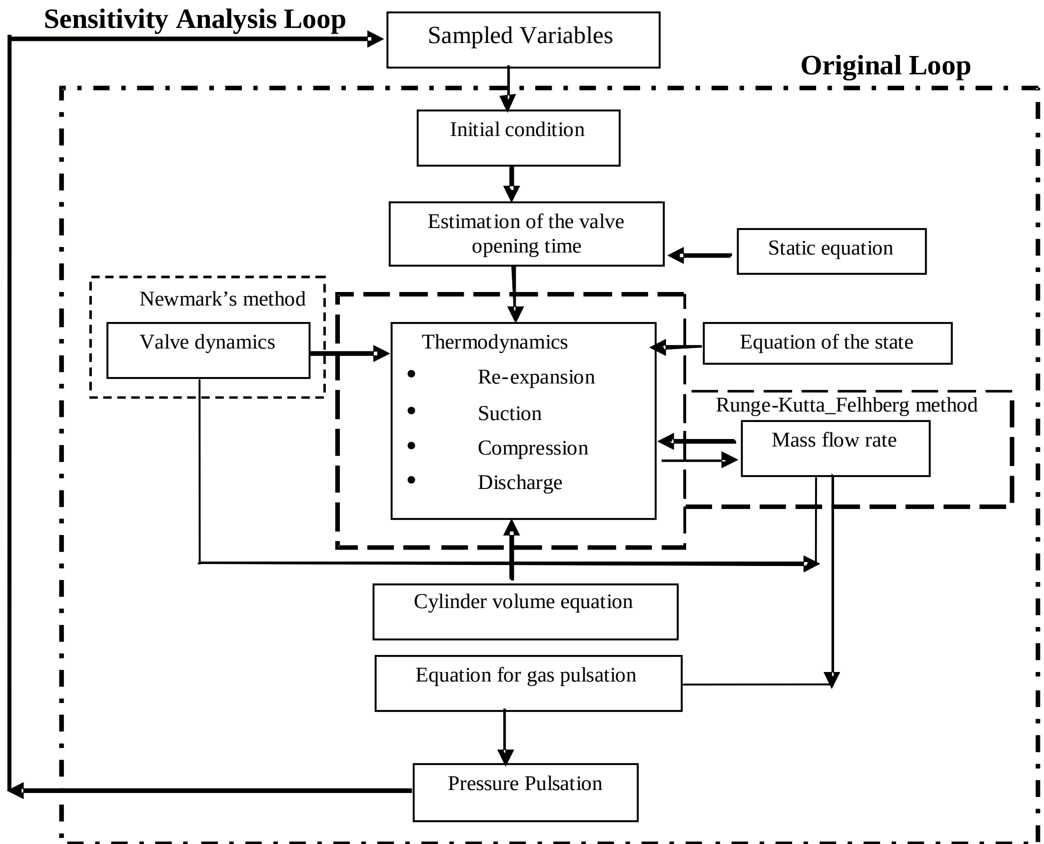

Figure 1: Simulation model showing sensitivity analysis loop outside the original loop.

For the initial study of uncertainty analysis, 19 variables in all were selected from the two simulation models. These variables are explained in Table 1 and Table 2. Many different combinations of these variables were studied to examine the relationship and contributions of each individual variable. For the results shown below, seven variables were chosen from model 1 which are: length of the 1^{st} section of the suction valve, width of the 1^{st} section of the valve, width of the 2^{nd} section of the valve, valve thickness, clearance, modulus of elasticity, and spring stiffness. The output from this model was then used as input to the second model where, in the first case, no change was made and, in the second case, only the manifold radius was changed. Initially 50 samples of the variables mentioned above were generated using Latin Hypercube Sampling Technique, using a uniform distribution for all variables. After running the computer program, the gas pulsations for each of the six valve locations were obtained for all the frequency ranges.

Table 1: Numerical Values of the Variables Used in Simulation I

Brief Description of Variables	**Symbol**	**Numerical Base Value**	**Max Value**	**Min Value**	**Units**
Revolutions per minute	N	2000	1950	2050	revolutions per minute
Mass flow through compressor	M_c	90	85	95	kg/hr
Suction pressure	P_i *(abs)*	293000	285000	300000	Pa (absolute)
Suction temperature	T_i	8.9	5	15	°C
Discharge pressure	P_c *(abs)*	937000	910000	937000	Pa (absolute)
Discharge temperature	T_c	57	55	65	°C
Young's Modulus for the valve	E	$206*10^9$	$184*10^9$	$226*10^9$	Pa
Valve thickness	t_v	0.0003	0.00025	0.00035	m
Spring stiffness of the stoppers	k_1, k_2	$1*10^5$	$1*10^5$	$3*10^5$	N/m
Height of stopper/clearance	C_{lr}	0.00085	0.000765	0.000935	m
Diameter of suction port	D_{sp}	0.01	no change	no change	m
1st section valve length	L_1	0.009	0.005	0.013	m
1st section of the valve width	b_1	0.008	0.005	0.013	m
2nd section of the valve width	b_2	0.015	0.015	0.012	m

Table 2: Numerical Values of the Variables Used in Simulation II

Brief Description of Variables	**Symbol**	**Numerical Base Value**	**Max Value**	**Min Value**	**Units**
Radius of manifold	r	0.05	0.049	0.051	m
Thickness of manifold	t_m	0.014	0.011	0.014	m
Depth of manifold	b	0.027	0.024	0.028	m
Diameter of suction pipe	D_p	0.012	No change	No change	m
Damping	ζ	0.055	0.045	0.065	
Factor causing change in area due to depth change at a location	h_b	0.013	0.011	0.015	m

9. SIMULATION RESULTS

One of the objectives was to identify the combination of the values of the input variables that produce the maximum and the minimum gas pulsations. In Fig. 2 (a) the maximum and the minimum values of the gas pulsation were located.

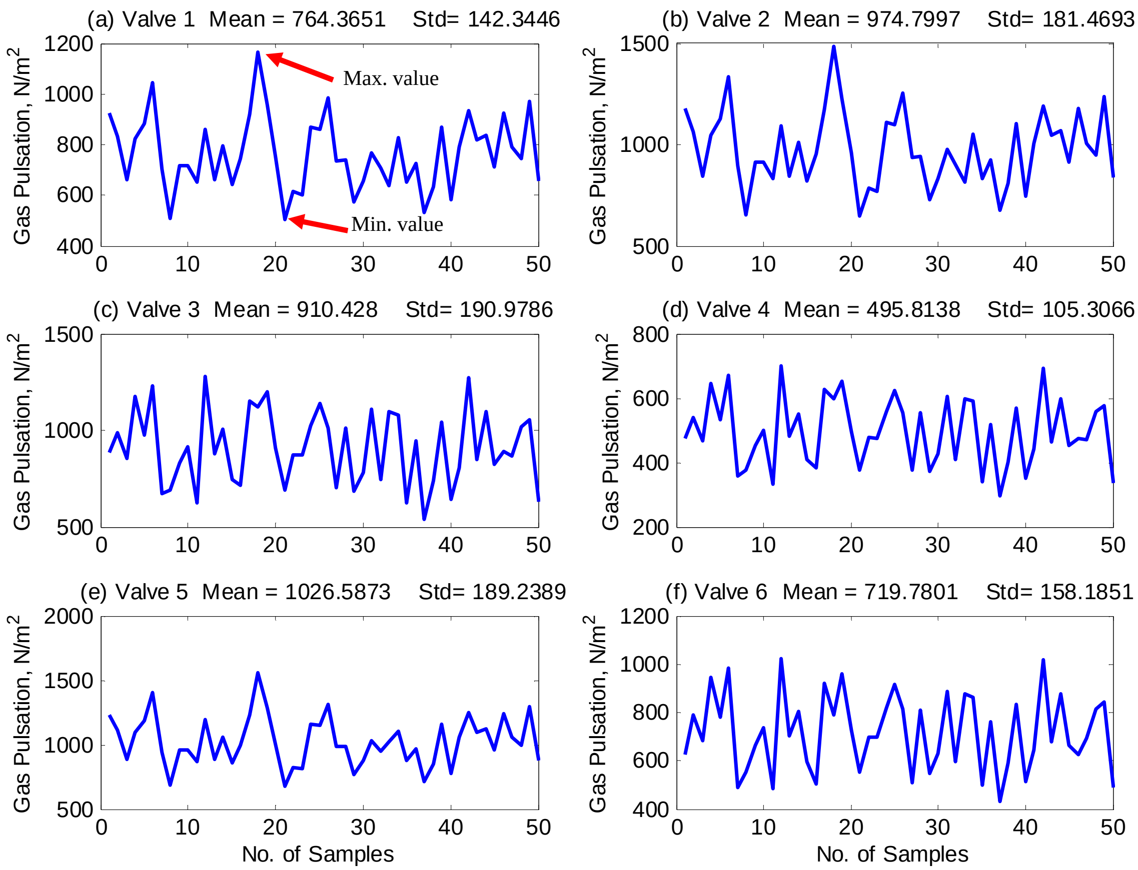

Figure 2: (a)-(f) Gas pulsation in the suction manifold without change in radius at various valve locations.

The study then focused on finding the combinations of input variables causing low and high gas pulsations. Since the original input vector was saved, the actual values of the design and operational parameters that produce these pulsations were extracted. The two such data sets are shown in Table 3 and Table 4.

Table 3: Set of Parameters Resulting in Minimum Value of Gas Pulsations

1st section valve length (m)	1st section valve thickness (m)	2nd section valve length (m)	2nd section valve thickness (m)	Valve thickness (m)	Clearance (m)	Modulus of Elasticity N/m^2	Spring Stiffness N/m
0.012831	0.010856	.019	0.015143	0.00032628	0.00080122	2.1952E11	1.2392E5

Table 4: Set of Parameters Resulting in Maximum Value of Gas Pulsations

1st section valve length (m)	1st section valve thickness (m)	2nd section valve length (m)	2nd section valve thickness (m)	Valve thickness (m)	Clearance (m)	Modulus of Elasticity N/m^2	Spring Stiffness N/m
0.01136	0.0092726	.019	0.017975	0.00033982	0.00090743	2.1702E11	2.8662E5

From the earlier studies (Park, 2004a) it was found that the gas pulsations were maximum at the frequencies 433 Hz and 500 Hz. The histograms of gas pulsations at different valve locations were used to outline the behavior of the response at those frequencies, to determine the nature of the simulation output distribution and to bound the output for different groupings of model parameters. Distribution means and standard deviations were also analyzed. A relatively higher mean value indicates a strong influence of the variables and a relatively higher value of standard deviation means a strong interaction among the variables. It was observed that in most of the simulations, the values of the gas pulsations were over predicted. The main reason is that the two models, which are connected by the mass flow rate, are highly sensitive to the valve dynamics. Many other combinations of the variables were also simulated (all results not included in this paper) to understand and predict the behavior of the distributions.

In Fig. 3, the histograms of the gas pulsations for the above mentioned two cases are shown. In the Fig. 3 (a)-(f), the gas pulsations predicted are quite higher than the average values, which indicates that the parameters selected were strongly influencing the response. The reason is that the valve parameters were adversely affecting the entire response of the system and the entire model seemed to be unstable with respect to this variable. In the second case, the initial system output (from model 1) was the same but an additional variable of the suction manifold radius was also changed. In this case the overall response of the system only changed by a small amount, which indicates that the effect of the manifold radius on the overall response is small. Based on the results of these initial simulations, it was decided to first improve the valve dynamics model.

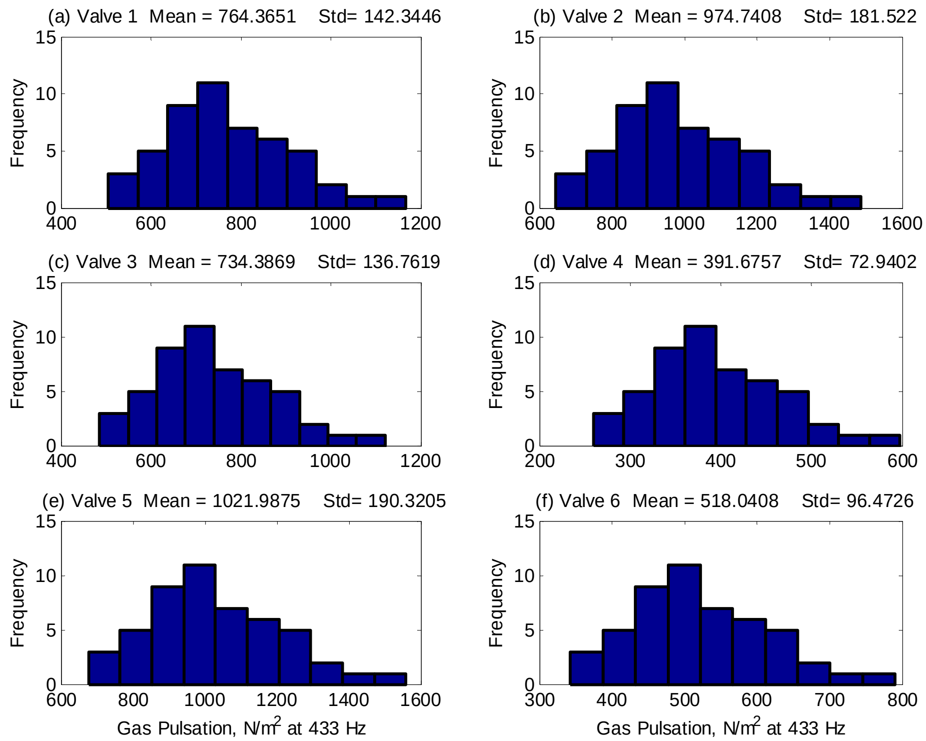

Figure 3: (a)-(f) Gas pulsation in the suction manifold without change in radius at various valve locations.

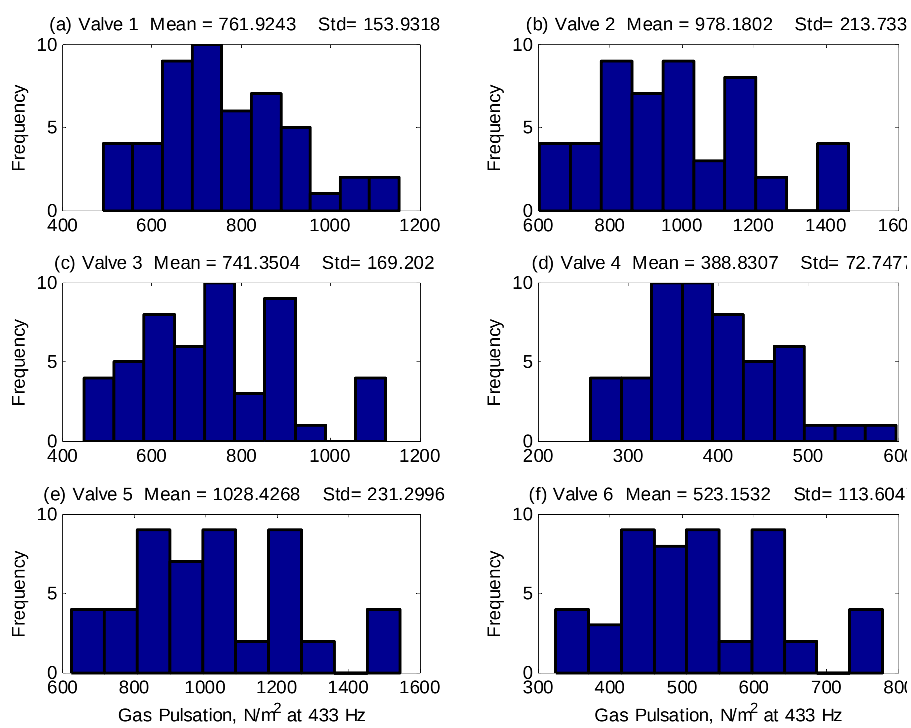

Figure 4: (a)-(f) Gas pulsation in the suction manifold with change in radius at various valve locations.

10. CONCLUSIONS

After running the initial simulations for many possible combinations of the input parameters the following remarks have been concluded:

- By using the UA procedure, two sets of data of operational and design parameters were generated, one resulted in lower value of gas pulsation and the other produced the higher value of gas pulsation. It is shown that by using the UA techniques, the right combination of input parameters that results in lower gas pulsations can be picked quite efficiently. Similarly, it is shown that what combination of input parameters results in higher gas pulsation, so that the designer can avoid such design scenarios.
- It was determined that the system was too sensitive to the valve dynamics which in turn also dictated the mass flow rate. It was decided that before applying further UA and SA techniques, this problem needs to be fixed. A two-dimensional valve model was developed (Park, 2006) to eliminate the effects of modeling approximations used in one-dimensional model. One major advantage of a two-dimensional model is that the parameters used for valve geometry can be eliminated from the UA and SA procedure. Moreover, the pressure parameters also become more stable.
- It was also concluded that instead of running the UA and SA techniques on the global model, these techniques would be performed at each sub-model first, and then integrated to the global model.
- The computational time needed to generate model predictions is very high, especially if the iterations are more than 20. This factor becomes more significant when there is a doubt about the effect of a distribution and different distributions have to be assumed to analyze their effects. It was also observed that the current code was quite inefficient and needs to be optimized to reduce the computational time.
- Compressor models show a strong nonlinearity as a small change in certain input variables such as rpm produces quite different results. So at times it is very difficult to determine which of the variables have negligible effects, linear or additive effects, or nonlinear and interactive effects.
- In using UA and SA techniques, there is no one particular method that works the best in all cases. In general, the use of two or more methods, preferably with dissimilar theoretical foundations has to be used to gain more confidence.

REFERENCES

1. Iman, R. L., Helton, J. C., 1981, An Approach to Sensitivity Analysis of Computer Models: Part I-Introduction, Input Variable Selection and Preliminary Variable Assessment, *J. of Quality Technology*, Vol. 13, No. 3, July 1981
2. Iman, R. L., Helton, J. C., 1981, An Approach to Sensitivity Analysis of Computer Models: Part II-Ranking of Input Variable, Response Surface Validation, Distribution Effect and Technique Synopsis, *J. of Quality Technology*, Vol. 13, No. 4, October 1981.
3. Iman, R. L., 1986, Modeling Input Processes, *Proceeding of the 1986 Winter Simulation Conference*.
4. Iman, R. L., 1987, Modeling Input to Computer Models Used in Risk Assessments*, Transactions of the American Nuclear Society*, Winter Meeting, Los Angeles.
5. Park, J., Adams, D. E., 2004, Numerical and Experimental Studies of Gas Pulsations in the Suction Manifold of a Multi-Cylinder Automotive Compressor, submitted for review to *Trans. ASME J. Vibration and Acoustics*.
6. Park, J., 2004, *Mathematical Modeling and Simulation of a Multi-Cylinder Automotive Compressor*, PhD Thesis, Purdue University.
7. Park, J., Adams, D. E., 2005, Gas Pulsation Reductions in a Multi-Cylinder Compressor Suction Manifold using Valve-to-Valve Mass Flow Rate Phase Shifts, submitted for review to *Trans. ASME J. Vibration and Acoustics*.
8. Park, J., Bilal, N., 2006, Development of a Two-Dimensional Finite Element Model of a Suction Valve for Reduction of Pressure Pulsation in the Suction Manifold of a Multi-Cylinder Automotive Compressor, *International Compressor Engineering Conference, Purdue University*.
9. Saltelli, A., Chan K., Scott, E. M., 2000, *Sensitivity Analysis*, John Wiley & Sons, Ltd.
10. Saltelli, A., Tarantola S., Campolongo, F., 2004, *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models* , John Wiley & Sons, Ltd.
11. Wyss, G. D, Jorgensen, K. H., *A user's Guide to LHS: Sandia's Latin Hypercube Sampling Software,* SAND98-0210.