Purdue University
Purdue e-Pubs

International Compressor Engineering Conference

School of Mechanical Engineering

2006

Optimization of Suction Muffler Using Taguchi's DOE Method

Sanjay S. Gosavi
Kirloskar Copeland Limited

Vinayak M. Juge
Kirloskar Copeland Limited

Mayur M. M. Nadgouda
Kirloskar Copeland Limited

Optimization of Suction Muffler using Taguchi's DOE Method

*SANJAY S. GOSAVI[1], VINAYAK M. JUGE[2], MAYUR M. NADGOUDA[3]

[1]Kirloskar Copeland Limited, Product Engineering Department,
Karad, Maharashtra State, India
Phone: +91 2164 241002 Fax: +91 2164 241122
E-mail: sanjayg@kircop.com

[2]Kirloskar Copeland Limited, Product Engineering Department,
Karad, Maharashtra State, India
Phone: +91 2164 241002 Fax: +91 2164 241122
E-mail: vinayakj@kircop.com

[3]Kirloskar Copeland Limited, Product Engineering Department,
Karad, Maharashtra State, India
Phone: +91 2164 241002 Fax: +91 2164 241122
E-mail: mayurn@kircop.com

ABSTRACT

The suction muffler of a hermetically sealed reciprocating compressor serves a dual purpose. It acts as a reservoir of the refrigerant and dampens the noise waves coming out through the gas path due to fluttering of the flapper valves. Thus, the suction muffler becomes a critical aspect of the compressor design process. The paper evaluates the effect of variables like length of the insertion tube, cross sectional areas of tubes, volume of expansion chamber, speed of sound in the refrigerant media etc. on functional parameters such as transmission loss characteristics and pressure drop across the muffler. The significance of the above variables in terms of the resulting parameters is decided by using Taguchi's DOE methodology. Optimization for acoustic characteristics is done using commercially available tool "SYSNOISE". The pressure drop characteristics of the muffler are analyzed using "FLUENT". The optimized muffler is validated experimentally using "Bench Test" in the laboratory. A fair agreement between the theoretical and sound test laboratory results is observed.

1. INTRODUCTION

The noise coming out of the hermetic compressor is related to the suction side, Discharge side and other electromagnetic components. Generally, the suction side noise is in the range of 50-1500 Hz, which is important from the perspective of the end user of refrigerator. This renders the task of designing a suction muffler much more critical and iterative as the pressure drop needs to be minimum on the suction side. An approach for designing suction muffler for a commercial refrigeration compressor model with R134a refrigerant is discussed in this paper. The parameters for the D.O.E. (Design of Experiments based on Taguchi approach) were selected based on primary calculations done using Vibro-acoustic and CFD tool for simulation of parameters like Transmission Loss(TL) and Pressure drop (ΔP) across the muffler. The whole analysis is carried out using CAE tools – PRO-Engineer for modeling the muffler, SYSNOISE for plotting Transmission Loss curve and FLUENT for calculation of Pressure Drop. This has given the flexibility of quick iterations with fair amount of accuracy as compared to the experimental results. The advent of these tools has helped in expediting the whole designing process maintaining its effectiveness as well as its purpose. The combination of software tools helps to reduce the number of physical prototypes for testing and also avoids the repetitious testing.

In this paper, the noise coming out from the suction side of the compressor i.e. the sound waves passage through the suction muffler of the compressor is discussed. The noise of a compressor is an assortment of different types of sound waves coming out from it. The noise can be categorized under two types –

1. Base Noise – Base noise is generated through following sources,
   - Valves through their impact in the suction and discharge stroke.
   - Imbalance in the shaft – rotor system.
   - Intermittent torque conditions in the motor.
2. System Noise – System noise is generated through following sources,
   - Suction and Discharge gas pulsations inside the compressor.
   - The tubes inside the compressor (e.g. shock loop) carrying the gas pulsations through them and transmitting the vibrations to the shell.
   - Mounting system of spring – mass type.
   - Shell Vibrations.

2. THEORY AND ANALYSIS

Sound Attenuation – Attenuation of the sound is the reduction of acoustic energy from entrance to the exit of the muffler tube.

Transmission Loss – Transmission loss through the muffler is the difference between the power incident on the muffler and the power transmitted through it. It is independent of the source as it is assumed that zero impedance i.e. constant pressure excitation prevails at the exit of the muffler.

2.1 D.O.E. Methodology

1. Following Parameters were Selected after brainstorming; affecting the attenuation characteristics and pressure drop of the muffler:
   a. Diameter of inlet and outlet tubes.
   b. Insertion length of the inlet tube.
   c. Number of holes on the outlet tube.
   d. Outlet tube hole diameter.
2. The orthogonal array of the parameters (L8 array at 2 levels) was prepared as shown in Table 1.
3. Each Trial was analyzed in SYSNOISE for Transmission Loss Curve. These TL curves were analyzed for the required criterion. As seen from Figure 2, Trial8 has the best TL curve.
4. The ANOVA table of the Trial8 combination prepared.
5. The response curves and the interaction effects plotted for Trial8.
6. The optimized combination of parameters was derived and then analyzed for the pressure drop in FLUENT.

Assumptions made for the analysis:

1. The sound pressures inside the muffler are small compared to the overall level of pressure inside the system.
2. Only plane waves of pressure are considered. (Imaginary/Complex waves are not considered.)
3. Viscosity effects of the fluid are neglected (The medium is inviscid and stationary).
4. The tailpipe of the muffler has its characteristic impedance value (ρ X C) i.e. it will act as a perfect absorber.

2.2 Governing equations:

The equations governing the flow of the sound waves through the suction muffler are the Mass continuity equation, Equilibrium equation and Energy equation. The generalized forms can be written as follows,

$$\rho_0 \frac{\partial \bar{u}}{\partial t} + \nabla p = 0$$ ………………………..Linearized Navier-Stokes Equation

$$\nabla^2 p(t) - \frac{1}{c^2}\frac{\partial^2 p(t)}{\partial t^2} = 0$$

……...…………………Wave Equation

where,
p = pressure acting on the particles
t = temperature of the ambience
ρ = density of the medium (0 suffix signifies the initial conditions)
u = velocity of the particles.
c = velocity of wave propagation.

The suction muffler is required to dampen the low frequencies ranging from 500 to 2000 Hz, which is the reason why a Helmholtz type resonator is chosen. A Helmholtz resonator has a small tube (neck) and a cavity. Here, the neck is represented by the holes and the cavity is the chamber volume of the suction muffler. The neck denotes the lumped inertance and acts as a resistance to the flow of waves. The neck also brings into account the inertial properties of the waves. The cavity denotes the lumped compliance and acts as a reservoir of acoustic energy. They can be represented in the Equation of Branch Impedance as follows,

$$Z_2 = \frac{\omega^2}{\pi c} + j\left[\frac{\omega \cdot l_{eq}}{S_n} - \frac{c^2}{\omega V_0}\right]$$

The resonance frequency where the transmission loss of a Helmholtz muffler is very high is given by,

$$\omega = \frac{c}{2\pi}\sqrt{\left(\frac{S_n}{l_{eq}V_c}\right)}$$

where,
l_{eq} = Length of the neck + 0.8 X $(S_n)^{0.5}$
S_n = Cross sectional area of the neck
V_c = Cavity volume

The amplitude of the above frequency is limited by the radiation resistance of the muffler. (i.e. the imaginary term in the equation of the branch impedance.)

To target the intended frequencies, the cavity size of the muffler was decided from the frequency equation and then the DOE Matrix was drawn to optimize the Transmission loss of the muffler. The aim of the exercise was to get a Transmission Loss Vs Frequency curve which should have following properties,

- It should indicate high amplitudes of the transmission loss (in dB) over a wide range of frequency in the low frequency zone (up to 1000 Hz).
- The transmission loss magnitudes in the high frequency zone (1000-2000 Hz) should peak at the desired resonant frequencies.

2.3 Method of plotting Transmission Loss curve in SYSNOISE

SYSNOISE uses Finite Element Method for the analysis of the gas passage through the muffler shown below in Figure.1. The cavity is modeled using solid modeling software. The cavity is then discretized in the 3-D element form using meshing software. The element type chosen is 3-D Tetra to achieve fast results with fair amount of accuracy. According to the theory, the pressures at the inlet and the outlet of the mufflers are calculated from the FEM matrix. These pressures are then divided and the logarithm of the division is taken to give the transmission loss across the muffler. The Transmission Loss curves are plotted for every experiment designed. The curves are then compared against the desired properties of the curve.

$$TransmissionLoss = 10\log\left(\frac{P_{inlet}}{P_{outlet}}\right)^2$$

2.4 DOE Matrix:

The following design optimization options were tried out.

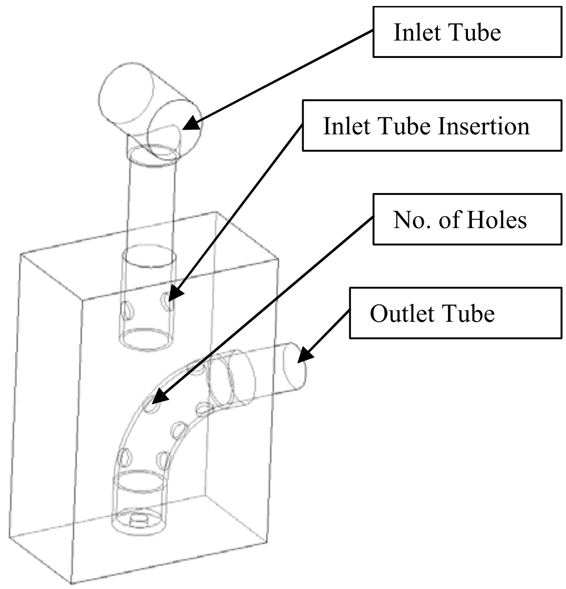

Figure 1: The Gas cavity model of the muffler

Table 1 : D.o.E. (L8 Array) Matrix of Parameters

DOE Trials	Parameters			
	Inlet & Outlet Tube Diameter	Inlet Tube Insertion Length	Outlet Tube Hole No.	Outlet Tube Hole Diameter
Trial1	ID1	IL1	N1	D1
Trial2	ID1	IL1	N1	D2
Trial3	ID1	IL2	N2	D1
Trial4	ID1	IL2	N2	D2
Trial5	ID2	IL1	N2	D1
Trial6	ID2	IL1	N2	D2
Trial7	ID2	IL2	N2	D1
Trial8	ID2	IL2	N1	D2

2.5 Results:

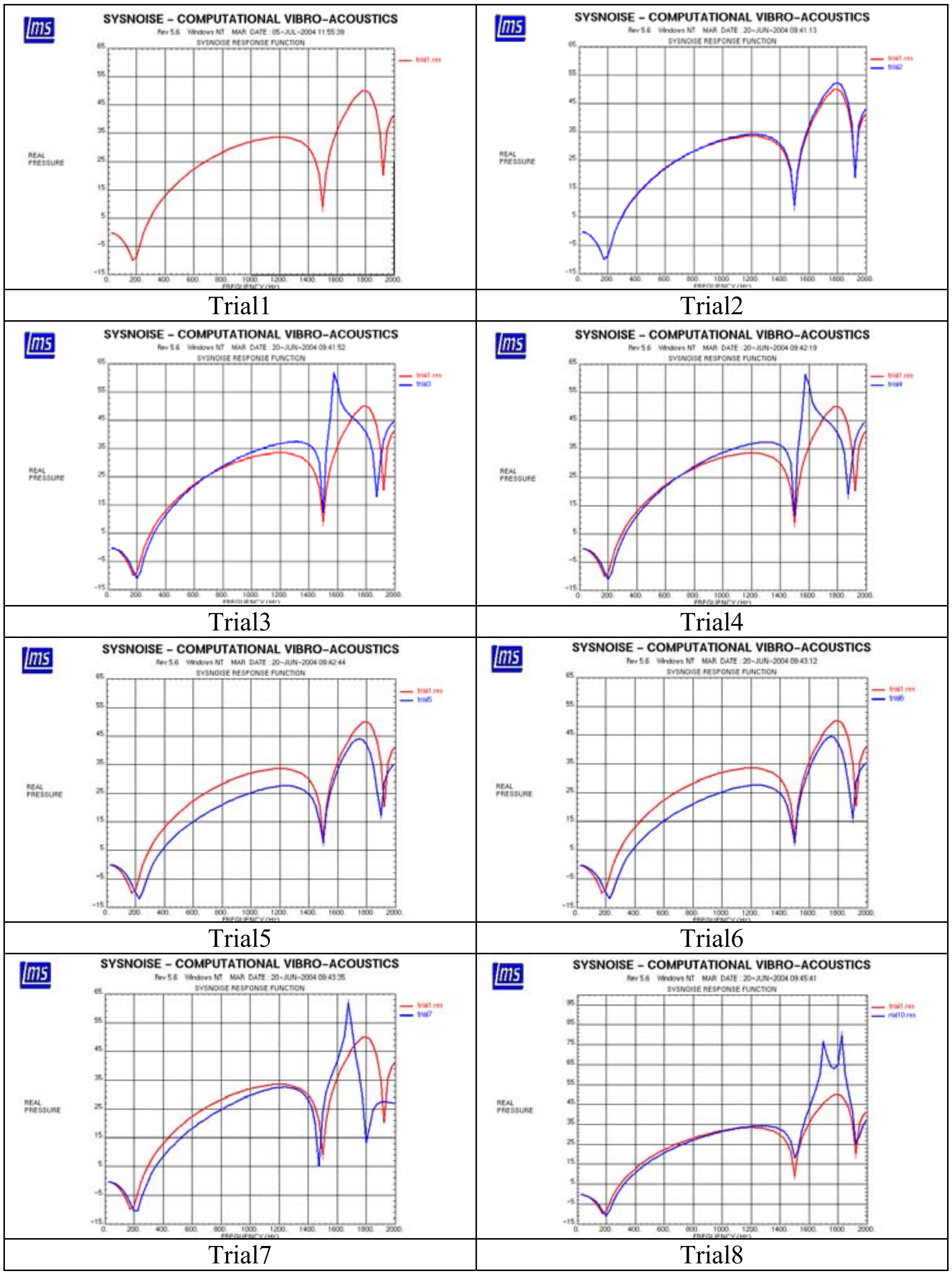

Figure 2 : Transmission Loss Curves for the trials

2.6 Discussion on the Transmission loss-TL Results:

1. As can be seen from the graphs for Trial1 to Trial 8, the variation in the outlet tube hole diameter has negligible effect on the magnitude of transmission loss.
2. Increase in the number of holes on the outlet tube gives better magnitude of transmission loss in the higher frequency range, although there is marginal decrease in performance in the lower frequency range.
3. Increase in the diameter of the tubes gives less magnitude of transmission loss in the entire frequency band.
4. Increase in the insertion length of inlet tube gives better magnitude of transmission loss in higher frequency range with marginal decrease in performance in the lower frequency range.
5. Also as seen from Trial7 and Trial8, increase in the insertion length of the inlet tube with number of holes kept the same, gives better performance in the higher frequency range without hampering the performance in the lower frequency range.

The results show us that the Trial8 muffler gives us the best results from the parameter analysis. The transmission loss characteristics of the muffler are as per the requirement. The muffler is further checked for the pressure drop characteristics to see the effect of the muffler on the compressor performance. This exercise in done in FLUENT software-CFD tool. This software uses Finite Volume Method to determine the pressures (of the fluid flow) at the inlet and the outlet of the muffler. These values are used to find the pressure drop across the muffler. This pressure drop is used in the equations of compressor performance. Here, the pressure drop across the new muffler is 10% higher than the existing muffler, but since the noise levels have shown a drop of 12% (4dBA Sound Pressure), this configuration is selected as a final design. The Figure.2 shows the pressure contours across the muffler as plotted in FLUENT.

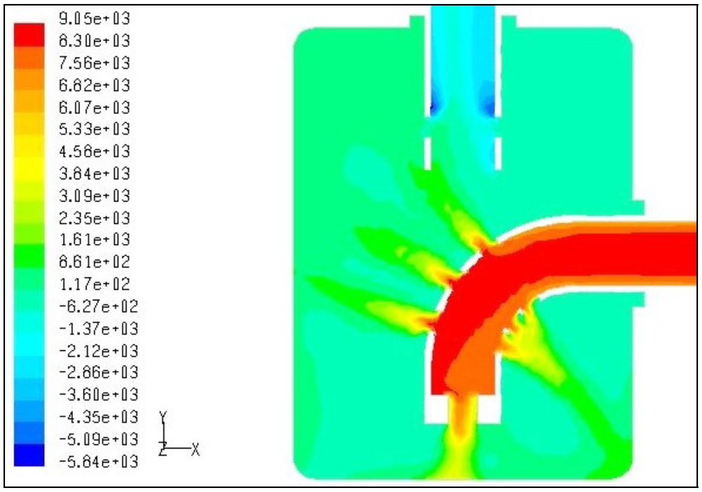

Figure 3 : Pressure Drop across the suction muffler

2.7 Experimental Validation of the Results

The method of experimental evaluation of the muffler using bench test in the laboratory can be given as follows,

- The experimental set up of the measurement of the transmission loss across the muffler (at the component level) is as shown below in Figure.4.
- The muffler is given a random noise at its inlet.
- The inlet probe is attached at the location where the sound waves just enter the muffler. This probe usually consists of two microphones placed one after the other to account for the two types of waves entering the muffler i.e. progressive and reflected.
- These sound waves pass through the muffler and the outlet pressure is calculated by the outlet probe attached at the location where the sound waves just leave the muffler.
- This data is stored in an instrument called FFT analyzer. FFT analyzer receives the signals from the inlet and outlet probes in time domain and converts them to pressure values in frequency domain.
- These values (pressures and frequencies) are plotted against each other to get the Transmission Loss Curve.

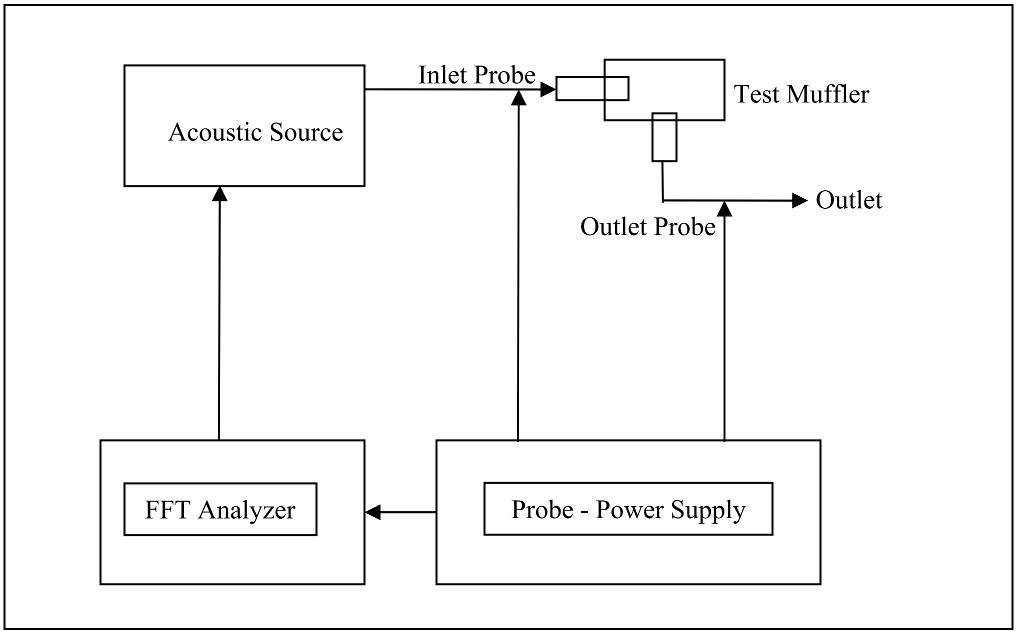

Figure 4 : Schematic Set-Up for Bench test of Suction Muffler

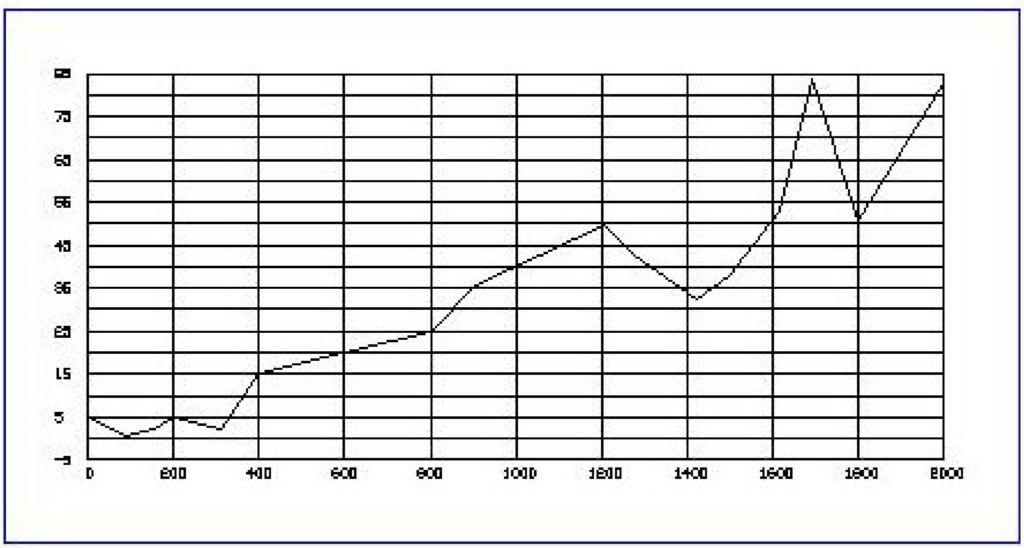

Figure 5 : Transmission Loss Curve for Trial8 from Bench Test

3. CONCLUSIONS

- From Figure 5, it is seen that the transmission loss curve plotted by the FFT analyzer is reasonably accurate with the curve plotted by the SYSNOISE.
- The difference in the magnitudes of the transmission loss is due to the radiation resistance of the muffler, which is neglected in the theoretical analysis. But, on a whole the signature of the curve remains the same.
- The Design of Experiments method of optimization and robust design has accelerated the process of muffler design by reducing the number of prototypes to be produced and the number of tests to be made for noise level and performance of the compressor. The exercise resulted in development of silent compressor meeting customer expectations.
- The agreement between the laboratory tests and CAE results has helped considerably in establishing approach for optimization of Suction Muffler .

REFERENCES

1. Lee, J. H., An, K., Lee, I., 2002, "Design of the suction muffler of reciprocating compressor", C11-5, *International Compressor Engineering Conference*, *Purdue University*
2. Masurekar, V. V., 1996, "Acoustics Three Dimensional Finite Element Analysis of a Muffler", Society *of Automotive Engineers Inc.*, 167-174
3. Young, C. I. J., Crocker, M. J., 1975, "Prediction of transmission loss in mufflers by the finite element method", *Journal of Acoustic Science of America*, 57, 144-148
4. Mongeau, L., Bolton, J., "*Fundamentals of Noise controls short course*", Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University,
5. Munjal, M. L., "*Acoustics of ducts and mufflers – with application to exhaust and ventilation system design*", John Wiley & Sons, New York, 1987, Ch.1 & 2, 1-102
6. Roy, R. K., *"Design of Experiments Using Taguchi Approach: 16 Steps to Product, Process Improvement and A Primer on the Taguchi Method"*, John Wiley & Sons, New York, 2001, 1-600
7. SYSNOISE 5.6, User Manual, LMS International, Belgium
8. Fluent 6.2, User Manual, Fluent Inc., USA