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# **DYNAMIC PARAMETER OPTIMIZATION OF AN AUTOMOBILE A/C COMPRESSOR USING TAGUCHI METHOD**

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## **ABSTRACT**

Taguchi Dynamic Signal-to-Noise (S/N) ratio and  $\beta$  analyses were applied to an automotive A/C compressor design to optimize the system performance. The method utilizes Taguchi design of experiment (DOE) strategy to identify and to optimize the significant parameters that affect the compressor performance. An eleven-factor array was used in the experiment. The DOE yielded the optimized combination of design parameters.

This paper discusses the ideal function of an automobile A/C compressor system and the parameters that affect its performance. It describes the techniques and methods used to optimize this compressor's performance, and gives experimental results and analysis.

## **INTRODUCTION**

There are many factors that will affect the performance of a compressor. Traditionally, the design is studied statically for performance (e.g. cooling capacity, horse power) and is measured against the change of one design parameter. Design curves are generated. This method suffers drawbacks. These are a) there is no interaction among different design factors considered; b) the noise factor is not included to study robustness (sensitivity) of system performance, and c) the experimental effort is greater and more time-consuming.

The Design of Experiment method, however, systematically studies all design parameters. In addition, the dynamic design of experiment method treats the system in study as an energy converter (in most cases, the systems are energy transformers such as compressors). To improve the robustness of the product performance, the Taguchi method is useful in that the method considers the noise factors as well as controllable design parameters. Furthermore, the method can identify areas of cost reduction in manufacturing without sacrificing the performance. In some cases, interaction among control and noise factors can be examined.

## APPROACH AND ANALYSIS

The basic steps of Taguchi robust DoE methodology are outlined as follows with the application to automobile A/C compressor system.

Step 1. Determine the relationship (ideal function) between input signal and output response of system

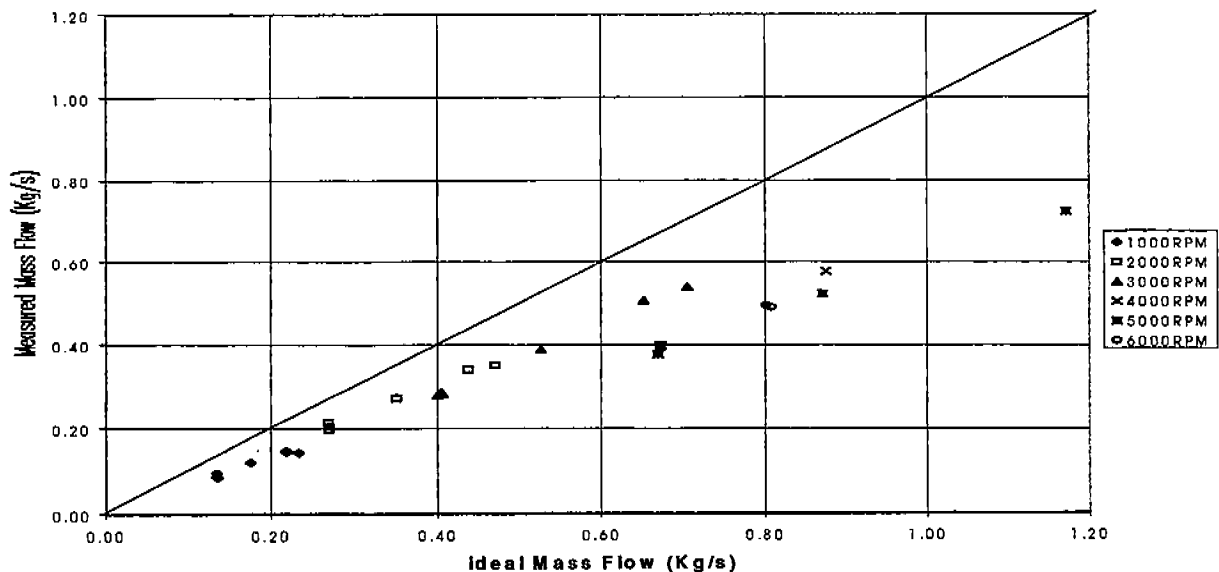
The compressor, which is the system under consideration in this study, has a function of compressing low pressure refrigerant vapor into high pressure vapor at the consumption of external power. The performance objective of the compressor is to utilize minimum power in order to achieve desired cooling capacity. Thus the output responses ( $y$ ) are the measurables such as mass flow rate (volumetric efficiency), horse power, coefficient of performance (COP), isentropic efficiency, etc. For the purpose of the study, mass flow rate, torque and discharge temperature are selected as ideal function parameters. For the input ( $M$  value), ideal values under a certain condition (head pressure and suction pressure/temperature) are used.

The ideal function for the A/C compressor is established as follows:

$$y = \beta M \tag{1}$$

where  $y$ = output responses (measured mass flow, torque and discharge temperature)  
 $\beta$ = coefficient, representing the efficiency of the system.  
 $M$ = input signals (ideal mass flow, torque and discharge temperature)

Equation (1) is verified by the experimental result shown in Figure 1. The objective is to minimize variability (robustness) and maximize performance ( $\beta$  value as large or small as possible).

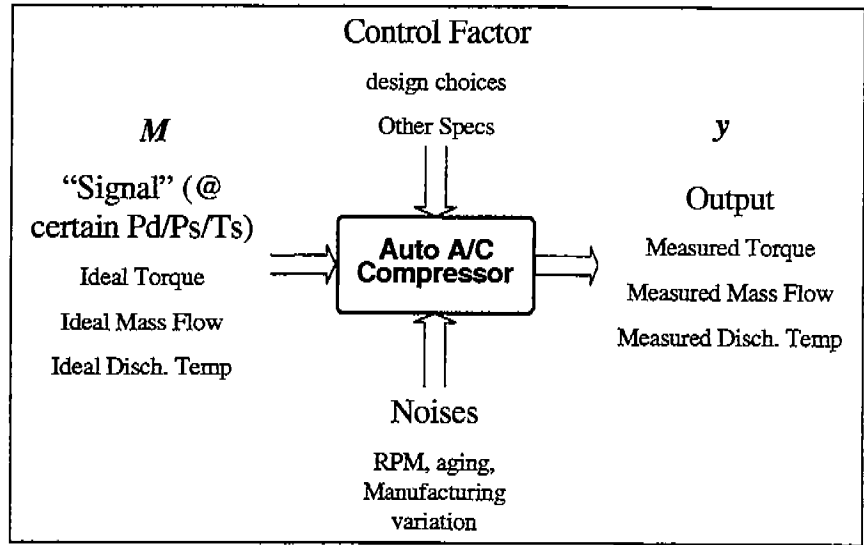


**Figure 1 Verification of Ideal Function (mass flow rate) for various RPM values**

Step 2. Identify Control and Noise Factors for system.

The control factors are those chosen by design. Clearances, fits and other design parameters affecting compressor performance are commonly used. The current study selects eleven parameters to fit Taguchi L12 matrix.

Noise factors are those uncontrollable or too difficult and expensive to control. Rotating speed varies for a conventional automobile A/C compressor, and is thus selected in this study as one noise factor. Aging, which relates to wear, fatigue and durability of the system, is another factor to be considered. The complete parameter diagram (known as P-diagram in robust study) is illustrated in Figure 2.



**Figure 2 P-diagram of Auto A/C Compressor System**

Step 3. Layout experiment matrix and conduct experiment.

L12 Taguchi orthogonal array is used in this study. Eleven factors (A through K), each of which has a (+) level and a (-) level, produce twelve experimental run (12 different compressor builds). Calorimeter tests are conducted to obtain mass flow, torque and discharge temperature at 3 signal levels (**M1, M2, M3**) for two different RPM (N-, N+). Figure 3 illustrates the matrix and experimental result (Torque values in ft lbf is shown here).

Compressor Build	Inner Array (Taguchi L12)											Outer Array					
	Control Factors											M1		M2		M3	
	A	B	C	D	E	F	G	H	I	J	K	N -	N +	N -	N +	N -	N +
1	-	-	-	-	-	-	-	-	-	-	-	14.34	16.32	9.69	10.89	10.48	11.57
2	-	-	-	-	-	+	+	+	+	+	+	14.53	15.98	9.81	11.01	10.74	11.88
3	-	-	+	+	+	-	-	-	+	+	+	14.99	16.39	9.49	10.62	10.49	11.98
4	-	+	-	+	+	-	+	+	-	-	-	14.34	16.16	9.72	9.76	10.53	11.42
5	-	+	+	-	+	+	-	+	-	+	-	15.68	16.73	10.08	11.44	11.15	11.57
6	-	+	+	+	-	+	+	-	+	-	-	15.14	14.22	9.71	9.03	10.53	11.78
7	+	-	+	+	-	-	+	+	-	+	-	14.18	16.07	9.81	11.15	10.33	11.61
8	+	-	+	-	+	+	+	-	-	-	+	13.78	15.75	8.98	10.92	9.55	11.56
9	+	-	-	+	+	+	-	+	+	-	-	15.13	16.90	10.37	11.86	11.05	12.43
10	+	+	+	-	-	-	-	+	+	-	+	15.16	16.89	9.94	11.33	10.89	12.04
11	+	+	-	+	-	+	-	-	-	+	+	15.59	17.13	10.74	11.85	11.47	12.51
12	+	+	-	-	+	-	+	-	+	+	-	14.24	16.67	9.60	11.64	10.13	11.58

**Figure 3 DoE Layout and Experimental Run (torque in ft lbf is shown)**

Step 4. Collect data and analyze the test results.

Data analysis allows for a prediction of the combination of levels for Control Factors that will result in a robust design. Dr. Taguchi developed a simple two step optimization procedure to determine the optimal combination of levels.

- Calculate the average S/N ratio for each level of factor, and select those levels that have the larger values of S/N ratio.
- Calculate the average Beta for each level of factor, and select those levels that have the larger (mass flow) or smaller (torque and discharge temperature) values of  $\beta$ .

Combining the selected factor levels leads to optimal/robust design of the engineering system.

Least square method is used to fit the linear curves ( Eq. 1) to obtain  $\beta$  and  $\sigma^2$  for each experimental run:

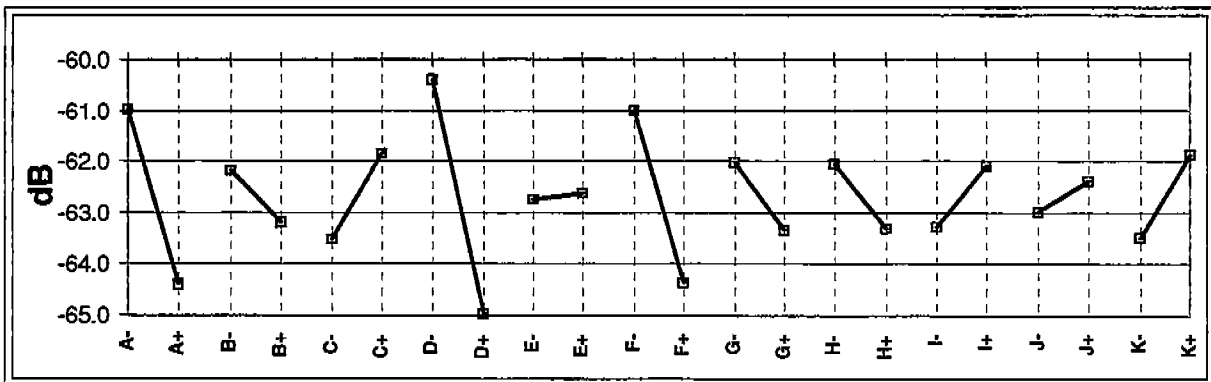
$$\beta = \frac{\sum^m \sum^n M_i y_{ij}}{\sum \sum M_i^2} \quad (2)$$

$$\sigma^2 = \frac{\sum^m \sum^n (y_{ij} - \beta M_i)^2}{(mn-1)} \quad (3)$$

where  $M_i = i$  th input signal value (ideal mass flow, etc)  
 $y_{ij} = ij$  th output response (measured mass flow, etc)  
 $m =$  the number of input signal levels  
 $n =$  the number of experimental measurement for each input signal level

And signal-to-noise ratio S/N, which is the measure of robustness, is obtained as follows:

$$S/N = 10 \text{ LOG}_{10} (\beta^2 / \sigma^2) \quad (4)$$



**Figure 4 S/N Effect Plot for Mass Flow**

Figure 4 and 5 demonstrate the S/N and  $\beta$  effects against factors for mass flow function. It is seen that performance (mass flow) is sensitive to factors A, C, D and F. For robustness, higher

values of S/N should be selected (A-, C+, D- and F-). Similar results are obtained for torque and discharge temperature functions.

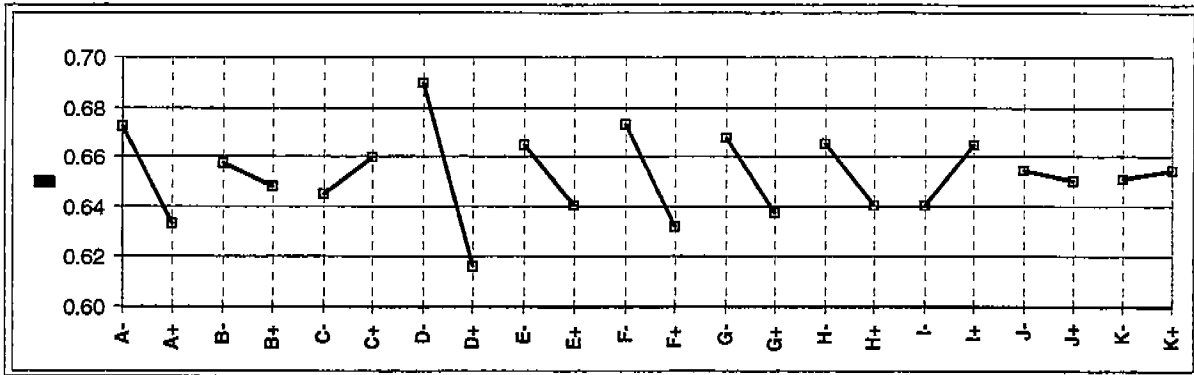


Figure 5  $\beta$  Effect Plot for Mass Flow

Step 5. Optimize the design based on S/N and  $\beta$  and Confirm the design

The optimized combination out of these eleven design factors considered for the compressor was then obtained by combining the selected factor levels. The levels with larger S/N and  $\beta$  values were selected: (A0, B0, C+, D-, E-, F-, G+, H-, I-, J-,K0), where A0 represents the mid-level between A- and A+ levels and so on. This design was fabricated, tested and used to confirm the validity of the predictions. The results are shown in Figure 6. The baseline is taken from the average S/N and  $\beta$  values for the initial L12 array. It is seen that the optimized design gained 3 dB in S/N and 8% in  $\beta$ . The gain for both prediction (P) and confirmation (C) are in agreement and the DOE is validated.

Mass Flow	S/N		$\beta$	
	P	C	P	C
Baseline	-62.7	-62.7	0.65	0.65
Optimal	-58.0	-59.8	0.72	0.70
Gain	4.7	2.9	11%	8%

Figure 6 Prediction and Confirmation of S/N and  $\beta$  Values for Optimized Design

\*Baseline: Actual Design Average  
 Optimal: A0B0C+D-E-F-G+H-I-J-K0

SUMMARY AND RECOMMENDATION

Systematic Taguchi robust design methods have been used to optimize an A/C compressor system. This system's ideal functions are determined, Noise and Control Factors and their levels are identified. A Taguchi L12 Orthogonal Array was laid out for experiments. Testing was completed and the results analyzed using the Two Step Taguchi Method to identify the Optimal design. Predictive analysis was completed and experiments conducted to confirm both the Optimal Design and the predictive analysis.

Another noise factor, wear due to aging, is being introduced by a special durability test on all twelve compressors. Once completed, the experimental run will be repeated to include this additional noise factor. Similar analyses will be made to assess the effect.

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