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Analysis of Rejection of Rotary Compressors in an Automobile Industry by Statistical Techniques

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***Abstract*- This paper deals with the study of rejection of rotary compressors in an Indian automobile industry. It is having a distinguished name in the field of manufacturing and exporting machined auto components and having ISO 9002 certification. The rejection cost of only rotary compressors of the industry was Rs. 9.06 lacs for the year 2014. Three statistical techniques: Pareto chart, paired comparison and full factorial design of experiments methods are used to analyze defect of rotary compressor. Through Pareto analysis, it is observed that the main cause of the rejection is the inappropriate air gap between stator and rotor. Some important parameters have been listed as suspect sources of variation to minimize the rejection of rotary compressors.**

***Index Terms*— Rotary compressor, air gap, Pareto analysis, Paired comparison method, Full factorial Design**

I. INTRODUCTION

Industries are using various latest statistical techniques and tools for improvement of their processes and products. The rejection level of the products can greatly be reduced by using quality tools like Six sigma, statistical process control (SPC), paired comparison, full factorial design of experiments and cause and effect diagram etc. Paired comparison method is used to analyze the data from experiments in which objects are compared in block size of two. One advantage of this type of design is that the differences in the outcome measures under one product treatment or the other; reflect only the effect of that product since everything else in the units receiving the treatments is absolutely identical. Pareto charts is used to identify the main causes that need to be addressed to resolve the majority of problems.

A. INDUSTRY AND PRODUCTS

This industry is one of the major industry; manufacturing and exporting automobile components and having ISO 9002 certification. It was established in 1997 and located at the northern part of the India. It has adopted latest cutting edge technology for manufacturing of precision machined components to cater to the needs of various industries. The integrated production system allows it to produce high quality, low cost products, and other original "precision forging technologies" and "global supply systems". The automobile parts; manufactured by this industry are: (i) planetary carrier (ii) support planet (iii) pin steering knuckle (iv) knuckle pins (v) oil filters (vi) tractor shafts (vii) rotary compressor (viii) differential housing and (ix) carburettors etc.

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The manufacturing process is shown with the help of flow chart that provides a visual representation of the process. Figure 1 shows the flow chart of the manufacturing process for rotary compressors.

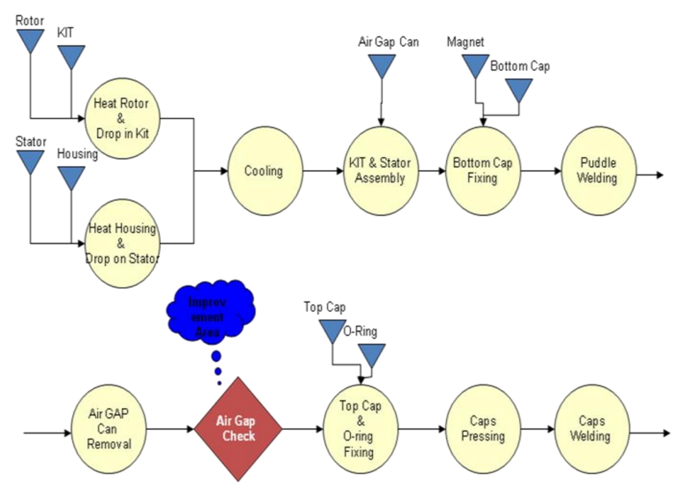

Figure1 Flow process chart of manufacturing of rotary compressors

II. NOMENCLATURE

Following symbols will be used in this paper:

n = Number of observations
S_d = Standard deviation of the sample differences
$\bar{d}$ = Mean of differences
BOB = Best of best
WOW = Worst of worst
DOE = Design of Experiments
ID = Internal Diameter
OD = Outer Diameter
PPM = Parts per million
v = Degrees of freedom
μ_d = Hypothesis for sample difference

III. LITRETURE REVIEW

Various researchers worked in this area and their contribution is summarized in this section.

Cheikh and McGoldrick [1] discussed the work, which was carried out in the area of tolerances with cost, function and process capability. So that the resulting functional variables of the assembly can meet their respective functional tolerances requirement and cost of manufacturing all the components to their respective functional tolerances is

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minimized. Glickman [2] stated that paired comparison data in which the abilities or merits of the objects being compared and changes over time can be modeled as a non-linear state space model. He concluded that when the population of objects being compared is large, likelihood-based analyses can be too computationally cumbersome to carry out regularly. His suggested method was evaluated on simulated data and was applied to ranking the best chess players of all time, and to ranking the top current tennis-players.

Shaw et al. [3] used optimization of experiments; used in drug discovery, can lead to useful savings of scientific resources. They considered the factors such as sex, strain, and age of the animals and protocol-specific factors such as timing and methods of administering treatments can have an important influence on the response of animals to experimental treatments. They concluded that a factorial experimental design approach is more effective and efficient than the older approach of varying one factor at a time. Sadagopan et al. [4] discussed about how General Electric, Motorola, and other top companies reported a substantial financial gain as a result of implementing the Six Sigma program, the momentum towards infusing it in an organizational. Thereafter, researchers working on Six Sigma program have reported its prowess. Prajapati and Mahapatra [5] discussed a very simple and effective design of proposed X-bar and R charts to monitor the process mean and standard deviation. The concept of the proposed chart is based upon the sum of chi-square (χ^2) to compute and compare the average run length values (ARLs). Kim et al. [6] attempted to minimize the thrust forces in the step-feed micro drilling process by application of the design of experiments (DOE) method. Taking into account the drilling thrust; three cutting parameters: feed rate, step-feed, and cutting speed were optimized on the basis of DOE method. For experimental studies; they presented an orthogonal array- L27 and analysis of variance (ANOVA). Based on the results, the sequence of factors affecting drilling thrusts corresponds to feed rate, step-feed, and spindle rpm etc. were determined. Brown and Peterson [7] suggested the method of paired comparisons to measure individuals' preference orderings of items presented to them as discrete binary choices. They reviewed the theory and applications of the paired comparison method, using a new computer program available for eliciting the choices, and presented an analysis of methods for scaling paired choice data to estimate an interval scale measure of preference.

Amlani and Schafer [8] presented an overview of the theoretical principle, paired-comparison strategies and associated approaches, the advantages of their methods, and recommended procedures for implementing the method of paired comparisons in the fitting of today's sophisticated hearing aids. Collins et al. [9] conducted experiments with multiple independent variables with the use of a complete or reduced factorial design. They advocated a resource management perspective on making the decision, in which the investigator seeks a strategic balance between service to scientific objectives and economy. They presented and compared four design options: complete factorial, individual experiments, single factor, and fractional factorial designs. Kukreja et al. [10] optimized the output feed rate of a stationary hook hopper feeder so that the best possible set of parameters can be selected to get the desired output. For this purpose the effect of various parameters on the feeder output were studied by them. They performed a series of experiments on the three process parameters to investigate the effect on the feed rate. To study the interaction among the factors; a full 23 factorial experiment approach has been adopted; using the two basic principles of experimental design-replication and randomization.

Zhang et al. [11] suggested various approaches for the calculation of z-score and error-bars. They summarized and compared various approaches on the basis of respect of theory, calculation complexity, and performances. They proved that generalized linear model with proper observation distribution setting provides the same results; derived from either traditional Thurstone model or maximum likelihood estimation model. Chiarini [12] discussed that Six Sigma is a well-consolidated model used by thousands of companies around the world and has a particular organization built on the define-measure-analyze-improve-control methodology.

Mishra and Sharma [13] proposed a conceptual framework for improving process dimensions in a supply chain network. They observed from the results that selection of appropriate strategies for improving process performance, based upon experiences and use of statistical tools by cross-functional teams with an effective coordination guarantees success. Prajapati [14] concluded that by using paired comparison technique; overall scrap (re-work) can be reduced from 15000 PPM to 2.5 PPM of two wheeler carburetor piston valves of an automobile industry; located in the northern part of India.

IV. ANALYSIS OF PROBLEM

The manufacturing process for rotary compressor is shown in Fig. 1. The main cause of the rejection of rotary compressors is inappropriate gap between stator and rotor that is measured with the help of feeler gauge. A feeler gauge is a tool; used to measure gaps. Feeler gauges are mostly used in engineering to measure the clearance between two parts. They consist of number of small lengths of steel of different thicknesses with measurements; marked on each piece. They are flexible enough; that even if they are all on the same hinge, several can be stacked together to gauge intermediate values. Figure 2 shows the gap checking process between stator and rotor with the help of feeler gauge.

Figure 2 Gap between stator & rotor

The details of rejection of rotary compressor for Dec., 2014 are as follows:

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(i) Number of rejected pieces of rotary compressor = 77
(ii) Number of scrap pieces = 25
(iii) Number of pieces that were reworked = 52
(iv) Scrap cost/piece Rs. 3000
(v) Total scrap cost = Rs. 75000
(vi) Rework cost/piece = Rs. 10
(vii) Total rework cost = Rs. 520
(viii) Total expected rejection cost per year = 75520 x12
= Rs. 9,06,240

A. PARETO ANALYSIS

This technique is used to identify the top causes that need to be addressed to resolve the majority of problems. Figure 3 show the Pareto analysis for different types of causes of rejection of rotary compressors.

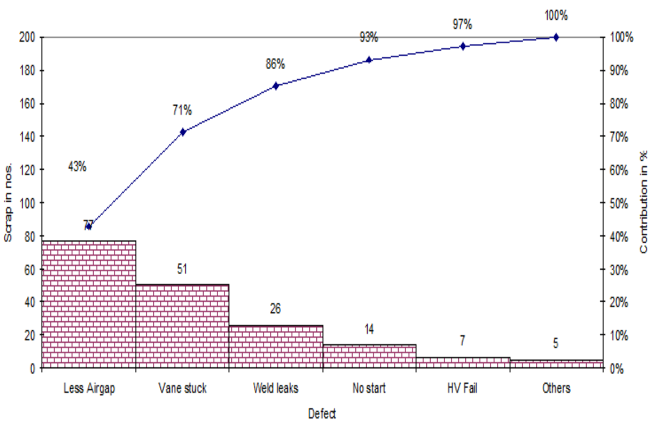

Figure 3 Pareto analysis

After analyzing the data of causes of rejection; it is clear that the maximum rejection was due to inappropriate air gap. Following components/processes are possible suspected sources of variation:

1. Individual Parts

Following probable dimensions are causing the problem

(i) Housing: Internal diameter (ID), Roundness / Taper

(ii) Stator: Internal diameter (ID), Outer diameter (OD) and internal diameter to outer diameter concentricity

(iii) Rotor: Outer diameter (OD), ID/OD concentricity, OD geometry (roundness, taper) step at lamination/end ring

(iv) Joint Kit: main bearing OD to crank shaft center line dimensional variations.

2. Assembly Process

(i) Housing to stator assembly
(ii) Rotor to kit assembly
(iii) Kit sub-assembly to housing sub-assembly
(iv) Puddle welding

B. ANALYSIS OF PROBLEM BY PAIRED COMPARISON METHOD

In this case study; data were collected for all the suspected sources. Various statistical methods are available but paired comparison method is used to analyze the problem to reduce the rejection of rotary compressors.

Paired comparison method helps to quantify the preferences of its members. It is generally used at the end of a brainstorming session, when trying to reduce a list to manageable size.

The data were collected from sources: housing, kit assembly, pump assembly without weld, pump assembly with weld and rotor with different parameters like inner diameter, roundness, Outer diameter, taper etc. The observations of various process parameters have been measured during their operations. From the collected data; eight best of best(BOB) and eight worst of worst (WOW) samples were taken for analysis by paired comparison method. Tables I shows the paired comparison of internal diameter (ID) of housing with eight best of best (BOB) and eight worst of worst (WOW) responses for analysis of air gap in rotary compressors.

Table I
Paired comparison of internal diameter (ID) of housing

Obns.	Housing ID (in inches)		Difference $d_i = WOW_i - BOB_i$
	WOW_i	BOB_i	
1	5.8971	5.8981	-0.001
2	5.9005	5.8981	0.0024
3	5.9007	5.8979	0.0028
4	5.8973	5.8997	-0.0024
5	5.8987	5.9003	-0.0016
6	5.9005	5.8987	0.0018
7	5.8985	5.8991	-0.0006
8	5.8963	5.9013	-0.005
			$\sum_{i=1}^{8} d_i = -0.0036$

Where i = 1,2,3……..8
Number of observations (n) = 8
Mean of difference $(\bar{d}) = \frac{d_i}{n} = -0.00045$

Standard deviation of the sample differences (S_d)

$$= \sqrt{\frac{\sum_{i=1}^{8}(\bar{d}-d_i)^2}{n-1}} = 0.17$$

Using t-test, at $\alpha = 0.05$, from t-distribution table; $t_{0.025} = 2.365$ for $v = n-1 = 7$ degrees of freedom. Therefore at the 95% confidence interval:

$$\bar{d} - t_{\alpha/2}\frac{S_d}{\sqrt{n}} < \mu_D < \bar{d} + t_{\alpha/2}\frac{S_d}{\sqrt{n}}$$

$$-0.1426 < \mu_D < 0.1417$$

The hypothesis for sample difference (μ_D) shows that there is no significant difference between two readings for internal diameter (ID) of housing of the rotary compressors, therefore it is concluded that this may not be the cause for rejection of rotary compressors.

Table II shows the paired comparison of housing-internal diameter (ID)-roundness with eight best of best (BOB) and eight worst of worst (WOW) responses for analysis of air gap in rotary compressors.

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Table II
Paired comparison of housing ID- roundness

Obsn.	Housing ID- roundness (in inches)		Difference $d_i = WOW_i - BOB_i$
	WOW_i	BOB_i	
1	0.0108	0.0068	0.004
2	0.0032	0.0086	-0.0054
3	0.0028	0.0065	-0.0037
4	0.0100	0.0094	0.0006
5	0.0088	0.0054	0.0034
6	0.0050	0.0084	-0.0034
7	0.0048	0.0070	-0.0022
8	0.0078	0.0048	0.0030
			$\sum_{i=1}^{8} d_i = -0.0037$

Number of observations (**n**) **= 8**

Mean of difference $(\bar{d}) = \frac{d_i}{n} = -0.00046$

Standard deviation of the sample differences (S_d)

$= \sqrt{\frac{\sum_{i=1}^{8}(\bar{d}-d_i)^2}{n-1}} = 0.012$

Using t-test, at $\alpha = 0.05$, from t-distribution table; $t_{0.025} = 2.365$ for $v = n-1 = 7$ degrees of freedom. Therefore, at the 95% confidence interval:

$$\bar{d} - t_{\alpha/2}\frac{S_d}{\sqrt{n}} < \mu_D < \bar{d} + t_{\alpha/2}\frac{S_d}{\sqrt{n}}$$

$$-0.010 < \mu_D < 0.0095$$

The hypothesis for sample difference (μ_D) shows that there is no significant difference between two readings for the housing internal diameter (ID)-roundness of the rotary compressors, therefore it is concluded that this may also not be the probable cause for rejection of rotary compressors.

Table III shows the paired comparison of housing-internal diameter (ID)-taper with eight best of best (BOB) and eight worst of worst (WOW) responses for analysis of air gap in rotary compressors.

Table III
Paired comparison of housing-internal diameter (ID)-taper

Obsn.	Housing ID- taper (in inches)		Difference $d_i = WOW_i - BOB_i$
	WOW_i	BOB_i	
1	0.0034	0.0026	0.0008
2	0.0016	0.0034	-0.0018
3	0.0046	0.003	0.0016
4	0.0042	0.0046	-0.0004
5	0.0034	0.0042	-0.0008
6	0.0024	0.002	0.0004
7	0.0036	0.0022	0.0014
8	0.0028	0.0018	0.001
			$\sum_{i=1}^{8} d_i = 0.0022$

Number of observations (n) = 8

Mean of difference $(\bar{d}) = \frac{d_i}{n} = 0.00028$

Standard deviation of the sample differences (**S_d**)

$= \sqrt{\frac{\sum_{i=1}^{8}(\bar{d}-d_i)^2}{n-1}} = 0.0012$

Using t-test, at $\alpha = 0.05$, from t-distribution table; $t_{0.025} = 2.365$ for $v = n-1 = 7$ degrees of freedom. Therefore, at the 95% confidence interval:

$$\bar{d} - t_{\alpha/2}\frac{S_d}{\sqrt{n}} < \mu_D < \bar{d} + t_{\alpha/2}\frac{S_d}{\sqrt{n}}$$

$$-0.00072 < \mu_D < 0.0013$$

The hypothesis for sample difference (μ_D) shows that there is no significant difference between two readings for the housing-internal diameter (ID)-taper of the rotary compressors, therefore it is concluded that this may not be the probable cause for rejection of rotary compressor.

Table IV shows the paired comparison of outer diameter (OD) of Rotor with eight best of best (BOB) and eight worst of worst (WOW) responses for analysis of air gap in rotary compressors.

Table IV
Paired comparison of outer diameter (OD) of rotor

Obsn.	Rotor OD (in inches)		Difference
	WOW_i	BOB_i	$d_i = WOW_i - BOB_i$
1	2.6125	2. 6121	0.00043
2	2. 6121	2. 6121	0.00000
3	2. 6126	2. 6122	0.00038
4	2. 6125	2. 6121	0.0004
5	2. 6121	2. 6124	-0.00027
6	2. 6129	2. 6128	0.0008
7	2. 6125	2. 6121	0.0004
8	2. 6121	2. 6129	-0.00088
			$\sum_{i=1}^{8} d_i = 0.00126$

Number of observations (n) = 8

Mean of difference $(\bar{d}) = \frac{d_i}{n} = 0.0016$

Standard deviation of the sample differences (**S_d**)

$= \sqrt{\frac{\sum_{i=1}^{8}(\bar{d}-d_i)^2}{n-1}} = 0.00173$

Using t-test, at $\alpha = 0.05$, from t-distribution table; $t_{0.025} = 2.365$ for $v = n$-1 = 7 degrees of freedom. Therefore; at the 95% confidence interval:

$$\bar{d} - t_{\alpha/2}\frac{S_d}{\sqrt{n}} < \mu_D < \bar{d} + t_{\alpha/2}\frac{S_d}{\sqrt{n}}$$

$$-0.0002 < \mu_D < 0.003$$

Since the hypothesis for sample difference (μ_D) shows that there is no significant difference between two readings for the rotor outer diameter of rotary compressor, therefore it is concluded that this may not be the probable cause for rejection of rotary compressors.

Table V shows the paired comparison of internal diameter (ID) of stator with eight best of best (BOB) and eight

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worst of worst (WOW) responses for analysis of air gap in rotary compressors.

Table V
Paired comparison of internal diameter (ID) of stator

Obsn.	Stator internal diameter		Difference $d_i = WOW_i - BOB_i$
	WOW_i	BOB_i	
1	2.65309	2.65361	-0.00052
2	2.65364	2.65361	0.00003
3	2.65377	2.65347	0.0003
4	2.65344	2.65394	-0.0005
5	2.65338	2.65371	-0.00033
6	2.65337	2.65346	-0.00009
7	2.65364	2.65340	0.00024
8	2.65338	2.65375	-0.00037
			$\sum_{i=1}^{8} d_i = -0.00124$

Number of observations **n = 8**

Mean of difference $(\bar{d}) = \frac{d_i}{n} = -0.00016$

Standard deviation of the sample differences (S_d)

$= \sqrt{\frac{\sum_{i=1}^{8}(\bar{d}-d_i)^2}{n-1}} = 0.00032$

Using t-test, at $\alpha = 0.05$, from t-distribution table; $t_{0.025} = 2.365$ for $v = n-1 = 7$ degrees of freedom. Therefore, at the 95% confidence interval:

$$\bar{d} - t_{\alpha/2}\frac{S_d}{\sqrt{n}} < \mu_D < \bar{d} + t_{\alpha/2}\frac{S_d}{\sqrt{n}}$$

$$-0.00043 < \mu_D < 0.0001$$

Since the hypothesis for sample difference (μ_D) shows that there is no significant difference between two readings for the rotor outer diameter of rotary compressor, therefore it is concluded that this may not be the probable cause for rejection of rotary compressors.

Table VI shows the paired comparison of outer diameter (ID) of with eight best of best (BOB) and eight worst of worst (WOW) responses for analysis of air gap in rotary compressors.

Table VI
Paired comparison of outer diameter (OD) of stator

Obsn.	Stator outer diameter		Difference
	WOW_i	BOB_i	$d_i = WOW_i - BOB_i$
1	5.90576	5.90572	0.00004
2	5.90588	5.90576	0.00012
3	5.90582	5.90599	-0.00017
4	5.90571	5.90529	0.00042
5	5.90553	5.90550	0.00003
6	5.90591	5.90599	-0.00008
7	5.90556	5.90570	-0.00014
8	5.90563	5.90574	-0.00011
			$\sum_{i=1}^{8} d_i = 0.00011$

Number of observations (n) = 8

Mean of difference $(\bar{d}) = \frac{d_i}{n} = 0.000014$

Standard deviation of the sample differences (S_d)

$= \sqrt{\frac{\sum_{i=1}^{8}(\bar{d}-d_i)^2}{n-1}} = 0.00019$

Using t-test, at $\alpha = 0.05$, from t-distribution table; $t_{0.025} = 2.365$ for $v = n-1 = 7$ degrees of freedom. Therefore, at the 95% confidence interval:

$$\bar{d} - t_{\alpha/2}\frac{S_d}{\sqrt{n}} < \mu_D < \bar{d} + t_{\alpha/2}\frac{S_d}{\sqrt{n}}$$

$$-0.00015 < \mu_D < 0.00017$$

Since the hypothesis for sample difference (μ_D) shows that there is no significant difference between two readings for outer diameter of stator of rotary compressor, therefore it is concluded that this may not be the probable cause for rejection of rotary compressors.

Similarly; paired compared technique is used for the rotor outer diameter (OD)-round, rotor outer diameter (OD)-taper, pump flatness before and after welding, housing to stator connection of rotary compressor, main bearing outer diameter to rotor connection etc. but no significant difference between two readings were found. That's why their calculations have not been shown in this paper. Since; paired compared technique does not provide the main causes of rejection; the full factorial design of experiment technique has been used for finding the main cause of the rejection of rotary compressors.

C. Full Factorial Design of Experiment

The full factorial experiment is an experiment whose design consists of two or more factors, each with discrete possible values or "levels", and whose experimental units take on all possible combinations of these levels across all such factors. This design may also be called a fully crossed design. These types of experiments allow the investigator to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. For the vast majority of factorial experiments, each factor has only two levels. For example, with two factors each taking two levels, a factorial experiment would have four treatment combinations in total, and is usually called a 2×2 factorial design. For this case study, following settings of parameters have been changed to reduce the rejection; as shown in Table VII.

Table VII
Setting of parameters to reduce the air gap

S. No.	Parameters	+1 Setting for BOB	*-1 Setting for WOW*
1.	Rotor OD	2.611 inches	2.613 inches
2.	Stator ID	2.655 inches	2.653 inches

From the factorial design analysis; it is found that the combination of maximum stator ID and minimum of rotor OD gives the best response. All those tables of responses have not been shown in this paper due to limitation of number of pages.

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Final recommended current and better conditions are listed in the Table VIII.

Table VIII
Current and better conditions of listed parameters

Parameters	Current Condition	Better Condition
Stator ID	2.651 inches	2.655 inches
Rotor OD	2.613 inches	2.611 inches

V. CONCLUSIONS

All parameters; which can cause rejection and rework were measured and analyzed in this paper. The paired comparison method was unable to identify the main cause(s) of rejection of rotary compressors. Pareto chart shows that the in-appropriate air gap between rotor and stator is the main source of rejection of rotary compressors. After using full factorial design of experiments; it is found that the in-accurate internal diameter (ID) of stator and outer diameter (OD) of rotor were responsible for less air gap in the defective components. It is concluded that the proper combination of maximum stator internal diameter (ID) and minimum rotor outer diameter (OD) can be used to eliminate the problem of air gap in the defective parts. It is found that after implementation of suggested solution, the percentage rejection of rotary compressors can be reduced to 5%.

For validation of improvement; better (B) v/s current (C) technique may be used as a future work. The limitation of the paper is that; only limited number of statistical techniques have been used for the analysis of rejection of rotary compressors.

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