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OVERVIEW OF ACCELERATED LIFE TESTING PROCEDURES FOR RECIPROCAL COMPRESSORS

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ABSTRACT

This article focuses on the understanding and discussion of accelerated life test (ALT) procedures applied to reciprocal compressors. ALT procedures were analyzed and classified according to time proportional and proportional hazard models. Many papers were published and extensive research has been done in the area of ALT procedures. However, the fast paced changing world demands for a new generation of ALT procedures that are able to give more detailed life estimates and focus on different compressor life periods beyond the warranty period. Leading compressor producers have know-how to succeed in this task, but the most successful ones will cover some basic tasks in the development of ALT procedures.

NOMENCLATURE

- $t$: time to failure
- $o, s$: subscripts for normal and stressed operating conditions
- $AF$: acceleration factor
- $R(t)$: reliability function
- $h(t)$: hazard rate function
- $L(\beta)$: partial likelihood function
- $\beta$: matrix of coefficients of acceleration factors
- $x$: matrix of stress factors

INTRODUCTION

The knowledge of the compressor behavior over time is a goal tracked by every single major reciprocal compressor manufacturer. It is also of relevant significance for the primary compressor users, appliance manufacturers. The quality of the compressor will substantially affect the performance of the final appliance system. Therefore, the reputation of a compressor or refrigeration system brand will be closely linked to an adequate compressor functioning over time. Additionally, an extended compressor functioning will lead to a reduction in the total life cycle cost.

The reliability of reciprocal compressors has become a leading field for compressor research. Quality control techniques are now known and have been shown to be efficient means to ensure quality at a short time horizon, allowing customers to focus on long term product quality features. Such features may be defined as product reliability measures. One of the main tools in the reliability field is accelerated life testing (ALT). These tests are designed to provide life estimates or to define lower bounds of product/parts reliability at shortened periods of time. Compressors are designed to last for several years. The fast changing world and demand for new and improved products urges the use of design techniques that help to reduce the product development cycle time without jeopardizing the quality of the design process. This makes ALT an essential part in the compressor design cycle.

Historical Facts in the Development of ALTs for Reciprocal Compressors

In the last decades, compressor manufacturers focused in the development of more efficient, less noisy compressors and in the evolution of their internal manufacturing processes. Robust materials, large safety margins
and a lower level of customer requirements assured the achievement of reasonable compressor reliability levels. During this period, some reliability tests were created to identify lower bound reliability limits, but they did not provide (if any) accurate life estimates. The previous experience had shown that if incoming models presented reliability test results equivalent to past models, therefore they would have achieved, at least, the same reliability performance.

The first breakdown to this approach happened in the 80's, with the necessity of replacement of CFC's systems. The dramatic changes in the compressor design and the implementation of several new design variables made traditional reliability tests to produce unusual outputs in terms of number of rejected units during the product development process. At the same time, appliance producers started to define more elaborated reliability requirements, that should be adequately demonstrated by the compressor's producers. A second convulsion in the development of ALT procedures is happening now, with the launching of new reciprocal compressor models, such as the variable speed compressors. Alongside, appliance manufacturers have also increased their coverage of product failures, multiplying their possibilities to a quicker and deeper comprehension of potential compressor reliability problems.

Observations of industry practices show that past industry experience in reliability is heavily based on trial-and-error test procedures. Most of the reliability research in industry still focuses on two distinct periods of the product life: the warranty period, where most of the failures are due to product malfunctions or quality related problems, and wear-out period, where the failures are due excessive wear and use. Few standardized life testing procedures (such as the ones defined by CECOMAF) are available for industry's use. Moreover, these conditions define clear conditions to test the product, but they do not enable the compressor producer to easily get compressor life estimates of a part or of the entire product. Such scenario creates an opportunity for the development of common ALT procedures aiming to define not only lower bounds of compressor life, but to allow producers to estimate the real life of the product under different stress levels or use's conditions.

Research Material - Background

The paper intends to briefly evaluate the state-of-art of compressor ALT procedures. Information used in this research was gathered from past publications (many of which are not cited here because they are reserved material) and from informal research of testing practices used among some major compressor manufacturers.

Publications of compressor ALT procedures are present in literature for many years. However, most of the published material normally does cover only reliability tests applied to compressor components, valid only under relevant assumptions or for specific scenarios. The publications established and consolidated useful information in the development of the tests, but the estimation life process is not normally defined. Therefore, the tests are able to only compare the reliability of different models for the testing conditions, without defining the expected life under normal conditions. Furthermore, there is normally only one stress level (which reduce the capacity of the life estimation process and diminish the power of checking the results validity) and important time and economic factors, such as number of tested units and when the test should be performed in the design cycle, are not revealed.

COMPRESSOR ACCELERATED LIFE TESTING - DEFINITIONS

It is reasonable to assume a reciprocal compressor typically presents three different operational life phases:
- infantile mortality or early operational life. During this period, the compressor experience high and decreasing failure rates. Most of these failures are due to manufacturing quality related problems or poor design decisions;
- approximately constant failure rate. After the end of the infantile mortality period, the compressor experiences randomness of failure occurrence, that are provoked by occasional exposition of the product to abnormal operating conditions or sporadic component failures;
- wear-out phase. At the end of the operational life, the compressor presents an increasing failure rate, due to its extended use over the years. Such use results in a degradation and aging process, which leads to the compressor failure mainly because of the presence of failure mechanisms associated with parts wear-out.
The predominant compressor failure mechanisms are normally different for each of these three operational life phases. Therefore, ALT procedures are different for every operational life phase and they are valid only for the failure mechanisms found in every phase.

With the actual stage of development of the compressors and considering the experience of ALT procedures that focus on the infantile mortality and wear-out periods, it is noticed an increased interest in the development of ALT procedures focusing at the constant failure rate phase. This phase is the longer in the compressor life and the extension of it will assure a larger positive impact in the product reliability. It is also important to point out that new ALT procedures should be designed aiming to provide life estimates instead of only lower reliability bounds, because compressor producers will also need to (quantitatively) demonstrate any compressor reliability improvement or status.

ALTs are applied to several compressor components. Some companies also apply ALT to materials and sub-parts at early design stages. "Table I" identifies the components more often submitted to ALT, as well as recognize the most used stress factors and applicability of the ALT in the compressor operational life.

Table I. Summary of most common ALT procedures: items, stress factors, and typical life period for the occurrence of a failure.

<table>
<thead>
<tr>
<th>Item</th>
<th>Typical Stress Factor(s)</th>
<th>Typical Life Period(s) of a Failure Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover / housing / external tubes</td>
<td>Vibration</td>
<td>Infantile mortality</td>
</tr>
<tr>
<td>Springs</td>
<td>Cylindrical mechanical load</td>
<td>Infantile mortality</td>
</tr>
<tr>
<td>Bearings and moving parts (piston, piston pin, valves, crankshaft, crankcase, etc.)</td>
<td>Temperature (oil viscosity), Pressure differential (equivalent to mechanical load), Rotation</td>
<td>Wear-out phase</td>
</tr>
<tr>
<td>Suction / discharge systems</td>
<td>Temperature, Humidity, Pressure differential, Vibration</td>
<td>All phases of operational life</td>
</tr>
<tr>
<td>Electrical motor (rotor, stator)</td>
<td>Voltage, Start-stop cycling, Temperature</td>
<td>Constant failure rate phase, Wear-out phase</td>
</tr>
<tr>
<td>Thermal protector / relay, PTC</td>
<td>Voltage, Start-stop cycling</td>
<td>Constant failure rate phase, Wear-out phase</td>
</tr>
<tr>
<td>Oil</td>
<td>Temperature, Humidity</td>
<td>Wear-out phase</td>
</tr>
<tr>
<td>Compressor (entire product)</td>
<td>Temperature, Vibration, Humidity, Pressure differential</td>
<td>All phases of operational life</td>
</tr>
</tbody>
</table>

Inputs for an ALT

Several inputs are needed to effectively design and conduct a compressor ALT:
- limit stress conditions, usually taken from experimentation or engineering analysis;
- compressor functioning conditions, taken from customer catalogs, application tests or field measurements;
- identification of effects, modes and causes of failure. This fundamental input may involve detailed engineering analysis of the physics of the failure and ultimately will define the type of acceleration factor;
- criteria for failure recognition. For most current compressor reliability tests, the test ends and the compressor is analyzed in order to determine if the product is failed or not, normally considering conservative failure criteria. For reliability purposes, it is always desired to obtain the maximum possible number of failures and to accurately
determine the time of the failure occurrences. Non-failed units (also called units with censored test time) are also helpful in the reliability determination, but a major effort should be done to reach the failed status. Therefore, a new approach (should be) is now being used in some companies: make the compressor reach a failed state, where the failures can be externally monitored without the interruption of the test. However, such approach may imply the use of correct reliability management practices, that need to overcome the internal resistance in change the failure criteria being used for years as well as to adequately address the issue with external customers. A practical justification for the use of external oversee of compressor failures is the fact that reciprocal compressors can not be internally checked when installed in refrigeration units and reported failures will be the sole perceptions of the end-user. In this sense, this new approach adequately fits into the end-user scenario.

ACCELERATED LIFE TESTING MODELS FOR COMPRESSORS

Compressor ALTs are classified into two different categories of applied stress:
- usage rate. In this category, the item is subjected to normal operating conditions, but at accelerated usage rate. For instance, 500,000 start-stop cycles test may be classified into this category of accelerated life test if the purpose of the test is to evaluate the start-stop system and an adequate cooling is provided in order to maintain normal operating conditions;
- usage stress. In this category, the items are subjected to harsh environment, with stress levels well beyond the normal operating conditions. The purpose of this test is to accelerate the occurrence of failures. The test results should be translated to normal operating conditions in order to determine compressor/parts life estimates.

Usage stress is the far most common accelerated type model applied in compressors. Usage stress models are also classified into time proportional and proportional hazard models. Therefore, a generic modeling for time proportional and proportional hazard models will be presented. Most of the current ALT procedures should fit in one of the presented models. Additionally, the acceleration factor for all these models is in the form

$$AF = e^{ax}$$

Time Proportional Models

Time proportional models present the following time to failure and reliability functions relationships:

$$t_o = (AF)t_s$$

and

$$R_o(t) = R_s\left(\frac{t}{AF}\right)$$

Time proportional models can be further classified into parametric-statistic-based models, physics-statistics-based models, physics-experimental-based models and degradation models.

Parametric-statistic-based models assume failure data follows a well-defined distribution, without any implicit physics relationship between the failure occurrence and time to failure. The use of ALT procedures of this type is not common because the results are only valid if the distribution selection is very appropriated and the designer has reached reasonable confidence degree in this selection.

Physics-statistics-based models assume the acceleration factor is proportional to the stress levels according to some physics derived relationship. Several ALT procedures used in the evaluation of electrical motors and oil types use this approach. The most common acceleration factors for this model are the Arrhenius model and the inverse power law.

Physics-experimental models are developed under the assumption that the failure mechanism follows a well-defined physics relationship. A typical example of application of this model is valve life test that employs Minor's rule to determine fatigue resistance and life expectancy in valves.
Degradation models are models applied to study degradation mechanisms during the compressor's life. There are very few reported ALT developments in this area, although compressor producers have shown interest in the degradational behavior of the compressor over time. The application of this model type will be boosted only when designers develop means to continuously watch the compressor functioning during the execution of an ALT.

Hazard Proportional Models

The application of time proportional models imply that the designer needs to assume some defined statistical distribution. However, for several ALTs, the following applies:
- Few test units are used, which makes the distribution fitting a risky task;
- The failure or censoring times do not fit adequately into a known distribution.

To solve this problem, non-parametric models have been developed. One of them, hazard proportional models, assume hazard functions are proportional at stress and normal operating conditions. Therefore,

\[ h_s(t) = (AF)h_0(t) \]

and

\[ R_s(t) = [R_0(t)]^{AF} \]

This approach does not require assumption regarding the use of any statistical distribution. It is a "free distribution" model. It is the only model that can provide life estimates for a product that has a "bath curve" shape in the failure rate function. A useful application of this model is in the development of ALT to evaluate oils and moving parts subjected to multiple stress levels and factors (temperature, pressure differential, humidity). The determination of the AF and \( \beta \) coefficients used in the model is done through the minimization of the following equation, known as partial likelihood function.

\[
L(\beta) = \prod_{i=1}^{r} \left( \frac{e^{\beta t_i}}{\sum_{j \in R(i)} e^{\beta t_j}} \right)
\]

where:  
- \( R(i) \) - set of unfailed components just prior to \( t_i \)  
- \( r \) - number of failed units in the test

Statistical Analysis

The design of an appropriate ALT procedure should always be related to the statistical planning and analysis of the experiment. The following guidelines apply to compressor ALT procedures:
- The designer should establish economical sample sizes but still powered enough to produce distribution fittings and data inferences at a reasonable range of confidence;
- The definition of the correct distribution fitting and accelerated life stress factor will define the guidelines for future data inferences. Therefore, it is important to adequately select models that will provide means to effectuate the desired analyses;
- Supportive statistical tools, such as design of experiments, should be more largely applied, because they may increase the designer's ability to make data inferences and optimize the use of testing resources;
- Statistical assumptions should be verified in all ALT procedures in order to validate the drawn results. This simple step can be easily forgotten in many applications.

Procedure for Compressor ALT

The analysis of the compressor and its parts reveals a complex set of environmental conditions. Based on the study of current and past compressor ALT procedures, the following rules apply to design an effective and efficient...
ALT program: definition of the testing purposes, analysis of product failures, field data and design specifications analysis, selection of a testing model (test conditions and sample size determination), statistical analysis of testing data, data inferences, and final conclusions or recommendations. The absence or underestimation of any of these tasks is likely to produce ALT procedures with low efficiency in the product life estimation process.

CONCLUSION

Extensive material has been published in terms of reciprocating compressor ALT procedures. Industry experience along the years created a know-how in the execution of ALT suited to their past necessities. However, a new boost in ALT development is now required: the creation of ALT procedures that are able to come up with more detailed life estimates and applicable to the new compressor developments and technologies.

As a result of this research, some areas were identified as potential areas for further development:
- application of planned statistical techniques to extend the designer's ability of draw conclusion from an ALT;
- study of strengths and weaknesses in each ALT model presented and cross this study with current practices to determine the best testing strategies;
- reliability management practices, with the definition of sequence, importance, resource allocation and impact of ALT procedures in the compressor development cycle;
- evaluation of reliability requirements of both customers and compressor producers in order to establish detailed reliability goals;
- study and implementation of revised and new standard ALT procedures to help to harmonize reliability demonstration among different compressor producers;
- management of field, test and reliability data, to minimize the use of resources in a company reliability program;
- study of stress levels and failure mechanisms in conjunction with statistical models to define the best ALT procedures for every component or the entire product;
- creation of ALT procedures aimed to produce life estimates, mainly during constant failure rate life period.

REFERENCES


