

Methodology for implementing accelerated life stress on stepper motors

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Abstract- In the industrial world the need to guarantee a long-life product becomes imperative. Life testing of electromechanical parts under nominal operating conditions may be time- and resource-consuming, making sometimes, such procedures expensive and impractical. As a result, technologies for accelerated life testing have been developed, to design high level stress tests (e.g. temperature, voltage, pressure, corrosive media, load, vibration, etc.). However, not all industries have access to the expensive equipment, such as thermal chambers and shakers, usually used for accelerated life tests. Hence, in this research, a methodology for implementing accelerated test by varying internal system variables is proposed and applied to a stepper motor. The issue of prediction accuracy associated with extrapolating data outside the range of testing, or even to a singularity level (no stress), has not yet been fully addressed. An increasing mechanical and thermal solicitation is evaluated in order to introduce an acceleration factor and to induce motor failure. The aim of this work is to estimate an ageing model to evaluate the life distribution in terms of time and stresses. The methodology is applied to stepper motors as a case study, some relevant experimental results are reported and commented.

I. Introduction

As well known, electronic and mechanical components, with stringent functional specifications (i.e. bearings, shafts, or gears), typically exhibit a high mean lifetime between failures. Therefore, life testing under operating conditions would require much time and resources. Accelerated Life Test (ALT) is a widely accepted solution to this issue in manufacturing industries since is used to expedite failures of a critical product in a short time period for predicting its reliability. Methodologies and applications concerning accelerated life testing have been proposed by a lot of Authors, as Nelson [1], Kececioglu [2], Lu and Meeker [3], Boulanger and Escobar [4]. These studies give a significant understanding on the modelling and analysis of accelerated degradation tests. In accelerated life testing there is always a number of key operating parameters that should be taken into consideration, however the overall severity level could result increased by the combination of them, motivating the formulation of new degradation models. Two main concerns have to be achieved in ALTs: on one hand, it is important that the number of accelerated variables be kept at a controllable level, on the other hand, questions often arise regarding the prediction accuracy when the nominal operating condition is more different from that one maintained during ALT.

The purpose of this research activity is to address the issue of ALT with extrapolation into nominal conditions. This is presented with the formulation of an accelerator factor in the Inverse Power Law (IPL) model to estimate the life distribution in terms of time and stresses. As a case of study, the proposed ALT methodology is applied inducing vibration on stepper motors. The stress instead that is generated artificially by a shaker, is determined by speed and current during motor operation in several conditions.

In Sec. II the proposed methodology is deeply described and commented, and the first results with relevant considerations are exposed in Sec. III.

II. The proposed methodology

Since many years by now, the manufacturers have been more and more interested to improve reliability and overall quality of new technological products. The requirements for higher reliability have increased the need for accelerated testing of materials, components and systems in order to compress time, so that relevant information can be obtained more rapidly [5]. This issue motivated research activities for the development of methods to assess the product life while reducing testing time.

There are different methods of accelerating reliability tests:

- *Increasing the use-rate of the item*, that is to increase the duty cycle of the product, which is adequate for products that normally are not in continuous use.
- *Increasing the stress level under which the item operates*, that is to increase the level of external variables like temperature or humidity to accelerate certain failure mechanisms such as chemical degradation.
- *Increasing the stress level of the item internal parameters*, such as voltage, current or other internal variables that could characterize the product behaviour and its life. Thus an item at high internal stress will generally fail more rapidly than it would have failed at lower stress.

The study of the failure histories of the device under test (DUT) is mandatory before selecting the proper accelerated life model and the stress to apply. As analysed in [6], the failures of motors are typically due to:

- Mechanical failures 83.45% (bearing failures 80.85%, others 2.60%)
- Electrical failures 16.55% (winding)

These results clearly indicated that a failure model for electric motors could be developed using two basic failure modes; i.e., bearing failures and winding failures. Besides bearing failures, mechanical failures include also, loose parts, broken terminals and rotors rubbing stator from improper assembly. In a normal population of motors the dominant failure mode would be the result of bearing failures. As a result of these considerations only bearing and electrical failures were analysed [7].

In order to develop single stress or multi-stress life models, it is necessary to establish the stress type and the combination or the sequence of stresses, then a model can be implemented that will be verified and validated by experimental observation.

For a preliminary evaluation of stepper motor response, a model with one stress variable (non-thermal stress) will be proposed, only in case of evidence relevant to thermal stress occurrence during the test execution, the model with two stress variables (thermal and non-thermal stress) will be considered.

The IPL is widely used to analyse accelerated life test data of insulating fluids, capacitors, bearings, spindles, and many other mechanical or electronic components, in order to estimate their working life when the acceleration operating parameters are non-thermal (i.e. speed, load, corrosive level and vibration amplitude), and it is formulated as below:

$$\eta(V) = \frac{1}{KV^n} \quad (1)$$

where $\eta(V)$ is the characteristic life under non-thermal stress only, K and n are fitting parameters. With accelerated life testing data, the IPL model provides the life probability distribution for electromechanical parts to fail at t ($t > 0$) under a particular stress V as:

$$f(t, V) = \frac{\beta}{\eta(V)} \left[\frac{t}{\eta(V)} \right]^{\beta-1} e^{-[t/\eta(V)]^\beta} \quad (2)$$

where β is a shape parameter independent of the applied stress level within the design limit. The value of β needs to be experimentally estimated [5].

In order to plan and implement quantitative accelerated life testing the steps presented in [8] were modified inducing the stress by internal parameters rather than by external equipment (thermal chamber or shaker). For the sake of clarity, the proposed methodology is to induce a vibration stress and, if possible, thermal stress on a stepper motor during operation condition in order to model the aging pattern by varying input variable of the motor driver. The vibration stress will be evaluated for different combinations of these variables, then the relative life-test acceleration factor will be calculated with reference to the vibration stress under nominal working conditions. The methodology developed for this study has two main advantages: *i*) let to implement the accelerated life test without expensive instrumentation; *ii*) to define the vibration signature of the motor in both nominal and accelerated life conditions; the latter feature could be useful to predict the ageing of the motor under test and to allow the prognosis and diagnosis, in a right way, for complex systems including this kind of motor.

III. Experimental results

Frequency domain analysis are very common in various field of interest, such as medical imaging [9] biomedical data analysis [10], industrial quality-control applications [11], characterization of systems [12], digital signal processing [13], waveform record characterization [14], power generation from renewable sources [15], and so on. During the last twenty years many techniques have been proposed in order to increase the accuracy of the estimations both for stationary [16], [17], and nonstationary signals [18] and to reduce the noise effects in internal anatomy investigation [19]. In this paper, an experimental setup was designed with the aim of monitoring vibration and thermal stress induced on the motor using a suitable frequency analysis. Speed and current were varied and the vibrations induced to the motors were monitored and recorded.

The measurements, in nominal and accelerated test conditions, were carried out in order to choose the test severities and to identify the reference values (the signature) for the final test configuration. Subsequently, at defined instants (t_1, t_2, \dots, t_m), periodical measurements and visual inspections will be performed to verify the operation of the DUT. All measurement values, at different instants, will be compared with the reference ones.

In order to measure vibration, a tri-axial accelerometer was placed on the motor and a simultaneous acquisition of all channels implemented. The sampled signals are denoted with the sequences $a_x[k]$, $a_y[k]$ and $a_z[k]$ according to the acceleration direction. The z -axis is vertical. All quantities are expressed as multiples of the standard gravitational acceleration g_0 . In the preliminary analysis the thermal stress was monitored by the use of an infrared camera.

The acquired vibration data were used to choose the test severities. In particular, the rms's of the accelerations, indicated as A_x, A_y, A_z , were calculated for the three axes. They represent the vibration stress that characterizes the DUT in the frequency range (0-1250Hz). Moreover the vibration stress on the motor in the frequency range (0,025-1000Hz) were calculated for the tree axes and indicated as A'_x, A'_y, A'_z . The reduction of the frequency range is due to a specific limit of the accelerometer bandwidth and to the choice to not consider the mean value of the vibration stress. In order to have parameters representative of the stress on all the axes the modules of the vector accelerations were calculated as:

$$|\mathbf{A}| = \sqrt{A_x^2 + A_y^2 + A_z^2} \quad (3)$$

and

$$|\mathbf{A}'| = \sqrt{A_x'^2 + A_y'^2 + A_z'^2} \quad (4)$$

The acquisitions of vibration stress were implemented in several operating conditions. In the nominal conditions the DUT follows a cycle in which speed is changed many times from zero to a positive value S and a negative value $-S$, with transients in which acceleration is uniform. S is defined in pulses per second, and is equal to 5 kHz. A second parameter that defines the nominal operating conditions is the motor current I , which is 0.7 A.

The duration of each test cycle in the preliminary data collection is about 15 s. As an example $a_z[k]$ in the nominal operating conditions is shown in Fig.1. The DFTs of $a_x[k]$, $a_y[k]$ and $a_z[k]$ in nominal conditions are shown in Figs. 2-4, respectively.

The vibrational stresses have been measured in several stress conditions, in which S and I are varied. In particular, S was set also to 7.5 kHz and 10 kHz, and I was set also to 1.5 A and 3 A. All combinations of the mentioned values for S and I have been experimented. In Fig. 5 the measured values of A_x, A_y, A_z are reported for all test conditions.

The data of Fig. 5 were used as a guide in order to define the conditions in which to implement the accelerated tests on several motors. Other factors that were taken into account were the possible limits of the test setup, the accelerated test model to be implemented, and the requirement to maintain small the sample size. As a result the following three tests were selected: $S = 5$ kHz and $I = 3$ A; $S = 7.5$ kHz and $I = 1.5$ A; $S = 10$ kHz and $I = 1.5$ A. The results of the accelerated test, quantified by the failures that will occur, will allow us to evaluate all the parameter characterizing the accelerated life model.

During the accelerated test execution, periodical functional measurements, as well as visual and manual inspections, have been established to verify the onset of relevant variations in the motor requirements or possible failures. In the first step of the experimentation no significant thermal variation on the motor has been detected.

IV. Conclusion

In this research, a methodology to evaluate the lifetime of an electromechanical component under accelerated

operating conditions has been proposed. Considering that the component life is an inverse power function of a non-thermal stress, a model is studied to predict the component's lifetime under accelerated operating conditions. By extrapolation, lifetime under normal use operating conditions will be estimated. ALT has been implemented after a first important step, consisting in a short measurement campaign. This step was fundamental in order to define the signature of the motor in nominal and different conditions, varying speed and current, and to choose the accelerated test severities. The first experimentation doesn't show interesting thermal variations of the motor when varying speed and current, but they will be included in the aging model if, continuing the experimentation, not negligible thermal stresses will appear. During the test, periodical measurements will be performed and then compared with the reference signature; each variation or failure correctly recorded will be of significant importance for the tuning of the accelerated life model.

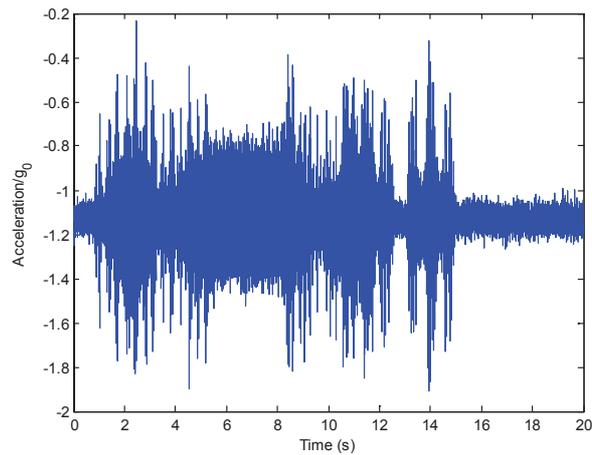


Figure 1. z-axis acceleration.

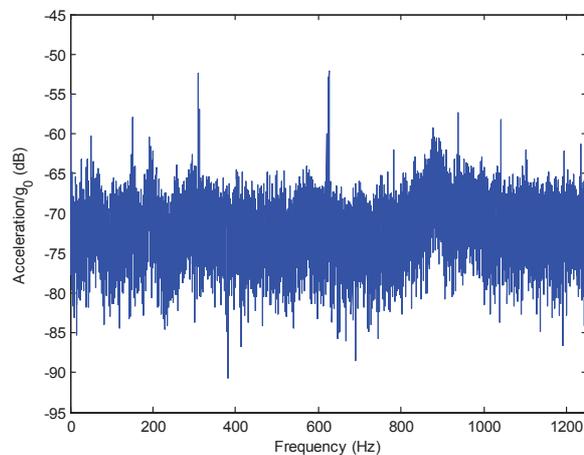


Figure 2. DFT of x-axis acceleration.

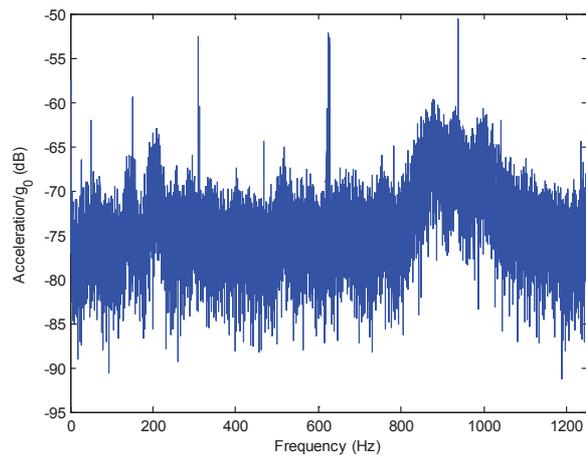


Figure 3. DFT of y-axis acceleration.

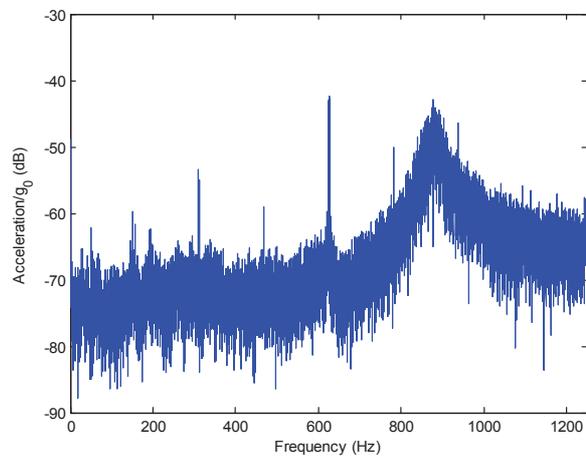


Figure 4. DFT of z-axis acceleration.

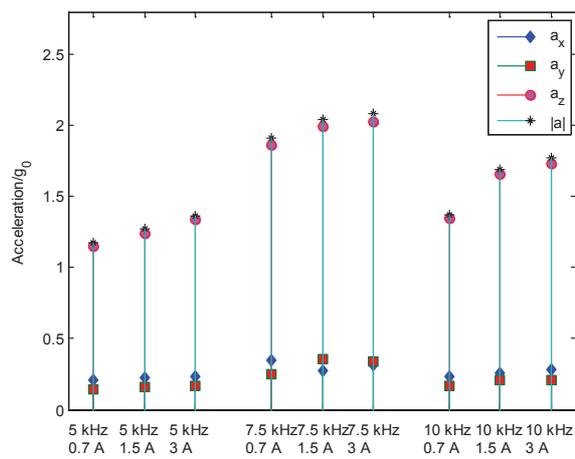


Figure 5. Acceleration in several test conditions.

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