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New reliability validation test for radial cooling motors – an oven home appliance application

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This paper presents the steps followed to define a new reliability validation test for shaded pole motors used in cooling systems of built-in ovens. The motors are fundamental for maintaining low temperature on sensitive components such as electronics, especially in high-temperature conditions such as pyrolytic self-cleaning, where the oven temperatures can reach up to 450°C. A Design of Experiment (DoE) approach was applied considering temperature, rotating speed and supply voltage as the key stress factors. Axial play, measured as the motor's movement along the shaft axis, proved to be a consistent indicator of upcoming failures. The test showed that temperature had the highest impact on mean time to failure of the component under investigation. Evaluating the acceleration factor using the Arrhenius model it was possible to propose a new test procedure achieving a 20% decrease of validation time while keeping the target of 90% reliability with a 90% confidence level. The stress-strength analysis showed that the cooling motor under study has a reliability of 99,55% over 10 years of usage in a pyrolytic oven, with a 90% confidence level.

Keywords: component reliability, stress-strength, shaded pole motor, accelerated life testing .

1. Introduction

The component under study is a shaded pole motor as actuator of the cooling fan for a home appliance built-in oven. The purpose of the cooling system is to keep the temperatures low in the upper and front area where electronics boards are installed.

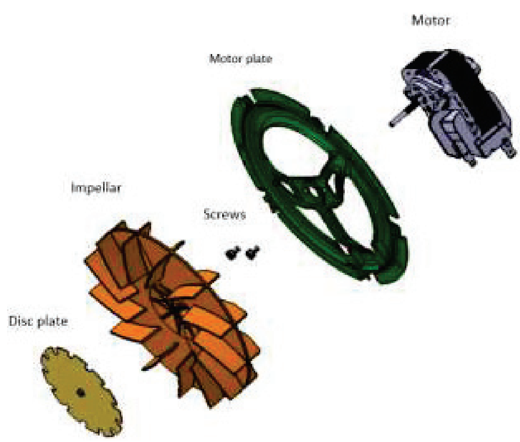

Fig 1.Radial cooling fan system for an home appliance built-in oven

While the appliance is working, the oven can reach up to 450°C (during pyrolytic self-cleaning). The electronic boards' overheating needs to be avoided in order to ensure a safe and efficient operation. The cooling motor is located on top of the oven cavity; its first purpose is to extract hot air and to blow it outside of the appliance through the cooling channel. The second purpose of the cooling system is to remove humidity from the cavity through the exhaust system.

The shaded pole motor is very common in the home appliance industries because of low cost, simple construction and reliability. Osheiba (1991) is providing a list of historical reference researches that started in 1930s. The calculation of the performance for a shaded pole motor is quite complex. Osheida (1991) reviewed and updated the calculations previous ideated by Kron (1950) and by Desay and Mathew (1971).

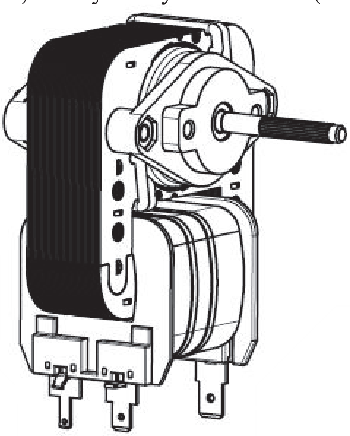

Fig 2.Shaded pole motor

The shaded pole motor has simple and reliable design, and it's been long used in multiple industries for low loads. In the figure below, the die-casting supports (2) have sliding contact bearings inside. The washer (3) and (5) and the spacer (4) keep the rotor and the shaft (6) in place. Stator (7), Magnetic Yoke Core (9.2), faston terminal (9.3), copper (9.4) are providing the alternate electromagnetic field to produce the output torque.

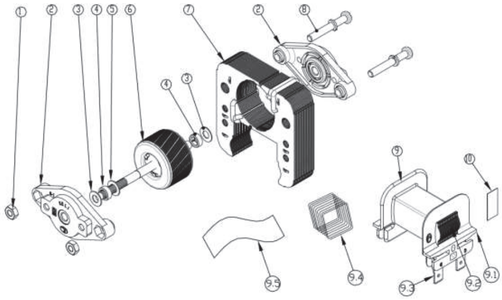

Fig 3.Radial cooling motor exploded view

The purpose of the experimental work described in this paper is to accelerate the component reliability test in order to have faster component validation. IEC 62506 (2013) - "Methods for product accelerated testing" - describes 3 types of accelerated tests:

- Type A: qualitative accelerated test. They identify the design weaknesses or manufacturing weaknesses
- Type B: quantitative accelerated test. They use quantifiable acceleration factors which are based on the physics of specific failure. In this case the stress level is increased during the test.
- Type C: quantitative time and event compressed test. In this case the stress is accelerated by the duration or the frequency of its application but not by the increase of the stress level

The test described in this paper is a mix of Type B and Type C.

2. Failure description

The asynchronous motor is frequently named induction motor (IEC 60050 (1990) - "Induction Machine – an asynchronous machine of which only one winding is energized").

IEEE Industry Applications Society Power Systems Reliability Subcommittee and IEEE Standards Board (1998) and Albrecht et al. (1986) reported that on average the faults occurrence are related to bearing in 45% of times, stator 30%, rotor 9% and others 16%. Kumar and Anand (2024) provided a wide review of induction motors faults. They listed the causes of the most frequent failure mechanisms.

The analysis in this paper is focused on the shaded pole motor, AC single phase asynchronous motor with a low-cost design. The failure mechanism analysed are the following:

- Interference between rotor ring and motor support, lead by the wear out of washers, producing a reduction of the motor performances and noise.
- Bearing misalignment that could increase the friction between shaft and bearing, influencing the overall motor performances (Minimum Starting Voltage and Speed)
- Debris produced by washers wear out affecting lubrication of the sliding contact bearing, increasing friction and ultimately leading the motor to stop.
- Possible fault at bobbin level, as a short circuit between coils due to the insulation copper wire degradation.

3. Design of experiment

Design of experiment (DoE) was conducted to define the main stresses that can lead to a failure in the motor: 3 factors applied in 2 levels:

- Working temperature. The 2 levels are chosen as the use temperature (common to most of the cooking functions) and an accelerated temperature.
  - i. 90°C, use temperature
  - ii. 120°C, accelerated stress
- Supply voltage. The 2 levels are chosen as the most common voltage and the accelerated voltage (not common).
  - i. 230V, nominal value
  - ii. 240V, accelerated stress
- Working Speed. The 2 levels are chosen as the use speed of the motor (common to most of the cooking functions) and the accelerated speed (used in some specific self-cleaning function like pyrolysis).
  - i. Low speed, nominal value
  - ii. High speed, accelerated stress

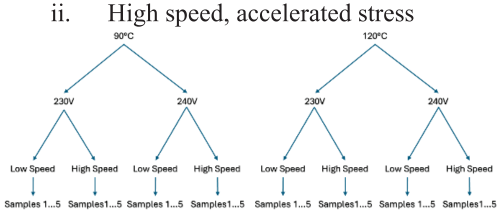

Fig 4.DoE - Combination of the factors

3.1. Test description

The motors have been placed inside a climatic chamber to replicate the oven conditions, following dedicated temperature cycles

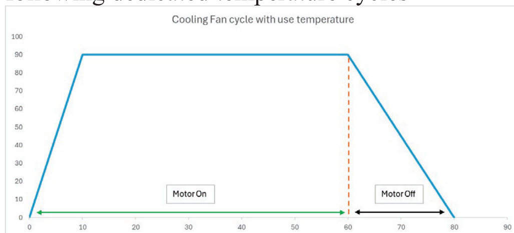

Fig 5. Use temperature cycle – 90°C

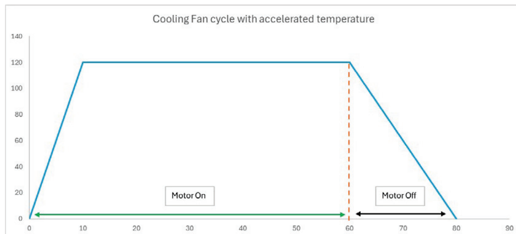

Fig 6. Accelerated temperature cycle – 120°C

The thermal cycle is composed by:

- Ramp up phase: the cycle starts at ambient temperature (20°C) and the motor is on. The temperature increases up to the target temperature (90°C or 120°C) to replicate the temperature changes in an oven. Total duration: 10 min
- Steady condition phase: the temperature inside the climatic chamber is stabilized at the target temperature and the motor runs continuously. Total duration: 50min;
- Ramp down phase: Last part of cycle, the motor is off and the temperature decreases from target temperature to ambient temperature.

To verify the reliability performance of the motors and their degradation, check points are performed: every 170 thermal cycles the test is interrupted for verification of the degradation metrics (speed, MSV, and axial clearance).

3.2 Degradation analysis

A key aspect of the test is to assess a potential degradation over the time leading ultimately to a failure. This enhances the possibility to shortening the test duration, enabling earlier prediction of failures. Several metrics were considered as best candidates to represent a possible degradation over the time leading to a failure:

- Speed of the motor (RPM). Most common metric, giving insight on mechanical and electrical health of the motor. A possible decrease in the speed can be a signal of increased mechanical resistance, electrical issues or lubrication issues
- Minimum starting voltage (MSV). Lowest voltage at which the motor can start rotating. It can be related to issues such as winding degradation or increased mechanical friction
- Axial Play. Movement along the motor's shaft axis. An increase in the axial play can be linked to bearing wear or degradation of internal components such as washers.

After 1020 cycles it is evident that while RPM and MSV remain stable over the time, Axial Play is constantly (linearly) increasing. With a regression analysis it is possible to evaluate the forecasted times to failure by calculating when the axial play will exceed the limit. This threshold results from measurements and from the distance between rotor rings and motor front support. Fig.7 shows the degradation curves most fitting the measurement points for all the samples under test.

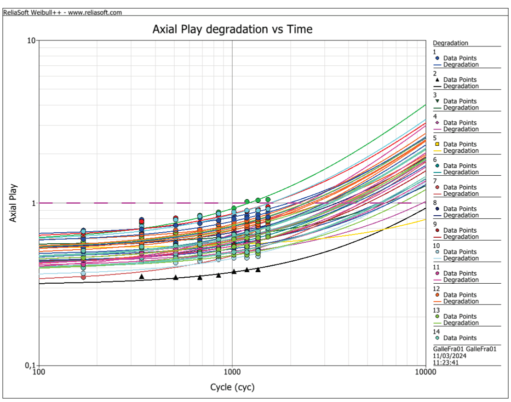

Fig 7. Regression curves of axial play measurement – logarithmic plot

The samples closest to failure showed a forecasted TTF of 1100, 1231 and 1431 cycles. All these samples belonged to the units tested at 120°C and high speed.

Experimental results confirmed these predictions. As soon as the axial play exceeded the limit, there was a sudden drop of RPM (as shown in Fig.8), meaning that failure initiated.

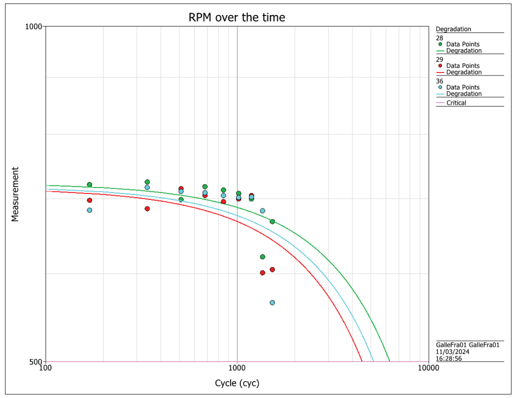

Fig 8. RPM measurements for motor predicted to fail at 1100, 1231 and 1431 cycles

The root cause analysis on the above mentioned failures has been performed. As visible in the picture of the Fig. 9, the die-casting support shows clearly the debris from the washer wear out leading to an increased friction and ultimately to a loss of performance of the motor.

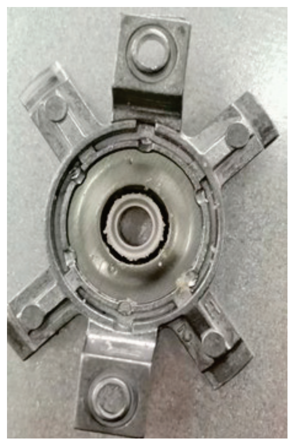

Fig 9. Debris from washer wear out after component failure

3.3 DoE results

Axial Play was selected as the metric to calculate the time to failures through the trend analysis as shown in Fig. 7. The pareto chart in Fig. 10 shows the effect of all the factors.

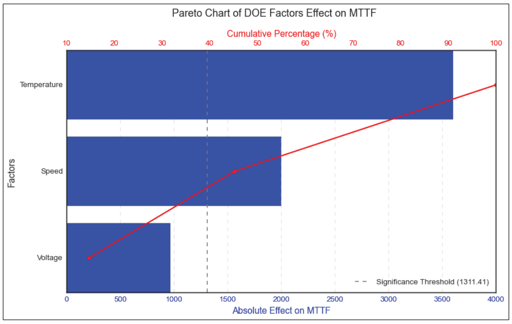

Fig 10. Effects of DoE factors on MTTF in component test

Temperature plays the most critical impact to the Mean Time To Failure (MTTF) – 3500 hrs between the average of the samples tested at 90°C versus the samples tested at 120°C. The speed has the second most relevant impact – 2000 hrs of difference in the MTTF between the samples tested at Low Speed versus the samples tested at High Speed. However, speed was not included in the final analysis since the stress level at component and application is not the same. At component level the motor rotates in free air, with a speed of 700 RPM (low speed mode) and 1000 RPM (high speed mode). In application instead working condition is different and nominal speed is 1050 RPM (low speed mode) and 2100 RPM (high speed mode).

Based on these results, focus was placed on the possibility to accelerate the test by increasing the temperature stress level.

4. Reliability analysis

The reliability analysis consists of 3 steps:

- Creation of a mission profile based on real usage of the oven home appliance
- Calculation of acceleration factors to relate real life working conditions with accelerated stress test results
- Stress strength analysis to predict long term reliability (10 years)

4.1. Mission profile determination

The working temperature and the speed of the motor are related to oven usage and which cooking functions customers usually select. This information is available through an internal survey and through data collected from connected devices as E. Belmonte et al. 2024 described.

The oven model selected is the one showing the most stressful collective load: a self-cleaning pyrolytic appliance. The self-cleaning is a pyrolytic function, with temperatures in the cavity reaching up to 455°C. In Table 1 is shown the summary of the most frequently used cooking functions and the related maximum temperatures recorded on the cooling motor.

Table 1. Cooking functions frequency, duration and maximum temperature measured on cooling motor

Cooking Functions	Frequency in 1 year (n°)	cooking function duration (min)	Maximum temperature of the cooling motor (°C)
Self-cleaning	8	90-150	100
Ventilated functions	121	30-50	90
Conventional cooking	71	40-65	85
Steam functions	60	30-50	85
Grill	22	20-40	83

While building the load profile it was considered that the temperature in working conditions is always equal to the maximum temperature. This assumption is conservative and helps simplifying the analysis.

4.2. Acceleration factor calculation

All life data from the DoE test was analysed with Reliasoft LifeStress folio®. Arrhenius is the most suitable model for evaluation of acceleration factor where the most relevant stress is temperature and, hence, it has been selected for the calculation in the case under study. Maximum Likelihood estimation was performed and lognormal distribution has recorded the best fitting of the life data. Arrhenius Lognormal distribution is the reliability model selected. The estimated parameters are reported in Table 2.

Table 2. Estimated parameters of Arrhenius lognormal model

Parameters

Model	Arrhenius
Distribution	Lognormal
Analysis	MLE
Log-Std	0,366297
B (°C)	288,476703
C (cyc)	231,135729
Ea (eV)	0,024859
Log-Mean (cyc)	8,648302
LK Value	-346,490721

Fig. 9 shows how the probability distribution of failures is dependent from the stress levels. The results are coming from the life data analysis of the DoE results, considering a confidence level of 90%.

Fig 9. Accelerated temperature cycle – 120°C

Using the Arrhenius model as reported, Eq.(1), it is possible to calculate the acceleration factors considering the reference stress level of 120°C (see Table 3).

$$AF = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_{acc}} - \frac{1}{T_{use}}\right)\right) \qquad (1)$$

Table 3. Calculated acceleration factors for the different use cases

Functions	max temperature of the cooling motor [°C]	Acceleration Factor
Self cleaning	100	1,62
Ventilated functions	90	2,23
Conventional cooking	85	2,69
Steam functions	85	2,69
Grill	83	2,92

4.3.Stress Strength analysis

Stress strength analysis is commonly used to calculate the probability of failure on the field. IEC (2013) illustrates that the intersection area between the probability density functions of stress and strength is representative of the probability of failure on the field. If the functions do not intersect, the probability of failure will be zero.

To perform the stress strength analysis, probability density functions need to be evaluated for the strength and for the stress. Considering that both the stress and the strength can vary over the level and the duration, then the probability intensity functions have been calculated at a fixed level named normalized level, that is 120°C in the case under study. Same approach has been performed by Miele et al. 2024 for the reliability analysis of a turn-table motor in oven home appliance application.

Stress strength analysis is executed via Reliasoft. Stress and strength are normalized to the value of 120°C, using the inverse of acceleration factors (see Table 3). The result of stress strength analysis is reported in Fig. 10.

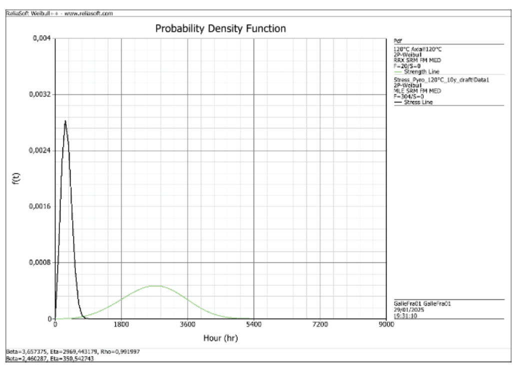

Fig 10. Accelerated temperature cycle – 120°C

The reliability of the cooling motor after 10 years of life in a pyrolytic appliance is 0,9955 considering the lower bound with a confidence level of 0,9.

5. New reliability validation test plan

In light of the acceleration factors obtained during component test and reported in TABLE 3, a new validation procedure is proposed. The proposed test is a demonstration reliability test based on the success run table reported in Table 4. Purpose is to demonstrate 90% reliability with 90% confidence level.

Table 4. Test duration in cycles for the reliability demonstration test

Sample Size	0 Failures	1 Failure	2 Failures
5	1628	2198	2852
10	1246	1552	1825
15	1087	1317	1507
20	993	1185	1338

The targets are expressed in cycles where the cycles are the same as the accelerated temperature cycles defined in Chapter 3.1 and showed in Fig.6.

6. Conclusion

This research provided some significant insights for the development of cooling motors for home domestic appliances.

Through a DoE it was established temperature as the primary stress factor affecting cooling motor reliability, with rotating speed as a secondary contributor.

Axial play emerged as the most effective indicator of potential failure of the component, giving a possibility to reduce testing time with the regression analysis of the measurements. This regression was further demonstrated with the evidence that predicted TTF were confirmed by test results.

Test to failure was executed at different stress levels, giving the possibility to estimate acceleration factors that can be used to further accelerate reliability testing. A new reliability test plan was proposed using the results of this study, leading to a reduction of 20% of the validation time.

The stress strength analysis methodology was applied on the normalized stress level of 120°C. The calculated reliability for the 10 years of life of the pyrolytic oven is 0,9955, considering the lower bound with a confidence level of 0,9.

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