Mechanical and Electrical Quality Control Tests for Small DC Motors in Production Line

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Abstract—**This paper describes the development and the first results of an automatic bench, designed to perform noise, vibration and electrical tests of small DC motors, to be placed at the end of production lines as Quality Control Tests. A prototype of the test bench and a data analysis method have been developed, trained with a small sample of known motors and used in a first measurement campaign. Testing procedures suitable to be implemented in production line environment with very high floor noise have been defined and the results are in agreement with the "good/faulty classification" made by expert operators working in production line. The testing procedures, sensors, data acquisition systems and data analysis will be the basis for a full automatic test station for small DC motors characterization to be placed in production line.**

I. Introduction

Permanent magnets DC motors are widely used in industry as they are lightweight, compact and easy to control in velocity, but also because they have a very simple structure and consequently an affordable price [1]. Small DC motors (10 – 20W) are largely employed in automotive and home appliances industries to drive fans in HVAC (Heating, Ventilation and Air Conditioning) systems. As they usually work at relatively high speed, higher than 1000 RPMs, they can produce noise and vibration that are perceived by the final user as a nuisance and as a lack of quality.

This problem is growing in importance in the automotive market with the advent of hybrid vehicles, in which the electrical motor is completely silent if compared to a traditional internal combustion engine, so all the other noise and vibration sources become noticeable by the passengers in the cabin and felt as a discomfort or a nuisance.

Motors manufacturers agree that problems related to noise and vibrations are rapidly growing in importance for their customers (e.g. car OEM or HVAC systems producers), which are constantly tightening their specifications and lowering the thresholds allowed in noise tests for motors homologation and final approval. These kinds of tests are usually performed periodically by manufacturers on a small percentage of motors coming from production line in anechoic chambers, in stated and repeatable conditions. They require a relatively long time and an extremely low background noise, typically below 20 dB (A).

When the product value is low as in this case (less than 10$), the manufacturing process is often not well controlled; consequently the characteristics and performances of the final product in terms of power consumption and noise produced can differ significantly among motors of the same model, even if assembled during the same work shift.

According to these premises, for motor manufacturers a fully automatic test bench to be inserted in production line able to perform electrical, noise and vibration quality control tests on the whole production would be desirable. However, the implementation of such kind of station is a critical issue, due to the high background noise and vibration coming from conveyors and other moving machineries along the line [2, 3] and to the very short time allowed for signal acquisition and process by production cycle time (6-8s). One of the challenges of the proposed solution is that the test bench has not to be completely insulated from the production line environment in order to keep its costs low and to not increase the complexity of the system.

At present noise tests of small motors in production line are made by expert operators which take the motor in the hand, put it very close to the ear and move it upside-down in order to simulate all motor possible mounting positions. That's because some defects are audible only when the motor is in a certain position as the weight of the rotor creates an unbalance that enhances the levels of noise and vibration produced when a defect is present and allow the operator to identify it.

It's easy to understand that repeatability in this kind of test is quite low, as test result is affected by operator judgment that depends on personal perception of the defect, tiredness, lapse in concentration, etc…

The main purpose of this paper is to define a procedure for the complete electrical and noise and vibration characterization of small DC motors, suitable to be implemented in a full automatic quality control test bench working in production line in order to reduce the subjectivity of the judgment and to increase its repeatability.

Noise and vibration measurements can be correlated in some cases, but are also complementary in others [4]. The choice to measure both quantities is mainly related to an improvement of the reliability of the test and to an increment of the number of information available in order to correlate different defects that can occur in these kinds of small motors.

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A preliminary study has been conducted to individuate the most significative quantities that must be monitored, where they have to be measured (e.g. noise close to bearings, close to the brushes, or both), and which are the parameters that can significantly affect the test results.

Together with noise and vibration, electrical characteristics of the motors are also important, in particular the current absorption and the RPM at each stated driving voltage.

A testing procedure has been hypothesized taking inspiration from the manual test now performed by operators, and a prototype test bench able to reproduce it in a semi-automatic way has been developed to perform a first campaign of tests.

First results on a sample of 50 motors are then presented and their correlation with expert operator's classification discussed.

II. Materials and Methods

A. Considerations on Quantities to Measure

According to the motor manufacturers and to literature [1, 5], the most significative quantities involved in the classification of the "quality" of small DC motors are:

- Current absorption (AC and DC)
- Driving voltage requirement
- Noise
- Vibration
- Rotation velocity (RPM)

The measurement of noise is critical, due to the high floor noise coming from moving machineries in production line that have a level of noise comparable to the noise emitted by the motor.

The measurement of vibration with an accelerometer is critical too, as the accelerometer cannot be fixed to the motor case with magnets that could alter the magnetic field of the motor stator and consequently influence the measure.

All the quantities are affected by the orientation of the motor in the space as in this lightweight components the weight of the rotor represents a not negligible force that is axial when the motor is in the vertical position and radial when it is horizontal.

B. Prototype Test Bench and Testing Procedure

The system is mainly composed by a drill mount plastic bracket equipped with a B&K single axis 4514-001 IEPE accelerometer for vibration measurement and two PCB 130D22 - ¼" – IEPE microphones for acoustic measurement. In this configuration the accelerometer is sensitive to the radial component of vibration that is usually dominant for small motors [5, 6]. One microphone is positioned on top, close the motor's shaft (Mic. UP) while another one is positioned next to the brushes holder (Mic. DOWN).

The bracket is fastened to a DC actuator that allows the rotation of DC motor under test around the y axis (see Figure 1). The angular position is monitored with a 2048 tick encoder.

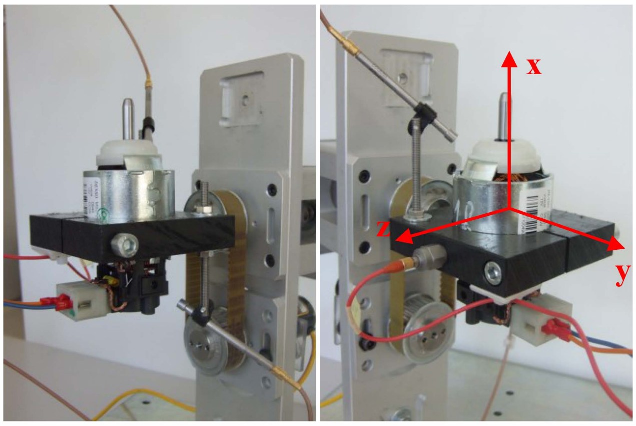

Fig. 1. Test bench realized: the motor is hold on a mount bracket and fixed with a clamp. The bracket can rotate around y axis.

Another B&K 4188 - ½" – IEPE microphone is placed above the test bench to monitor the floor noise in order to discard acquisition when the floor noise is too high or when disturbs occur. As mentioned before, one of the main challenges is to measure the noise of the motors in production without the use of a semi anechoic room that is too expensive and complex to be used in production, but just using a good sound proof chamber.

Current is measured with a LEM PR50 probe while driving voltage has been directly acquired from the power supply.

Tests have been conducted in laboratory, with an average floor noise of 52-54 dB(A), that is a condition similar to what can be reached in production line placing the test bench in a good sound proof chamber (RW = 30 dB(A)).

Signals have been acquired using a 24 bit National Instruments cDAQ data acquisition board (NI-9234) for accelerometer and microphones and a NI-9215 data acquisition board for all the other signals. Sample rate frequency was 51.2 kHz and proper anti-aliasing filters were used. A 10 Hz high-pass filter has been used to remove from acceleration signals the contribution of the rotation around the y axis.

The testing procedure has been stated as following:

1. The operator places the motor inside the bracket, closes it with the clamp and connects power supply
2. A constant voltage supply of 3 Vdc, which correspond to a rotation speed of about 1000 RPM, is applied to the motor
3. The actuator makes the mount rotate clockwise with constant velocity of 0.8 rad/s, after 180° it returns back.
4. The motor is switched off and the operator removes it from the bracket.

Each test has a duration of about 13 seconds.

The system has been trained using 15 motors, 6 good and 9 classified as noisy or simply "faulty" by expert operators in production line.

Another sample of 50 motors of the same model, 30 classified as faulty and as 20 good, has then been used in this test campaign to test the system.

C. Signal Processing and Features Extraction

The acquired time histories have been processed in order to extract the following features:

- Acceleration W(h) – weighted RMS value [7]
- Microphones overall noise level in dB(A) [8]
- AC Current RMS value
- DC Current value
- RPM, calculated from the first harmonic of the AC current FFT spectrum. Zero-padding [9] method has been used to increase frequency and RPM resolution.

Each acquisition has been divided in segments of 100 ms of duration and all the features listed above have been calculated for each segment and associated to the angular position of the motor obtained from encoder data. First graph on top of Figure 2 shows a typical graph of the angular position of the motor rotating around the y axis during the test.

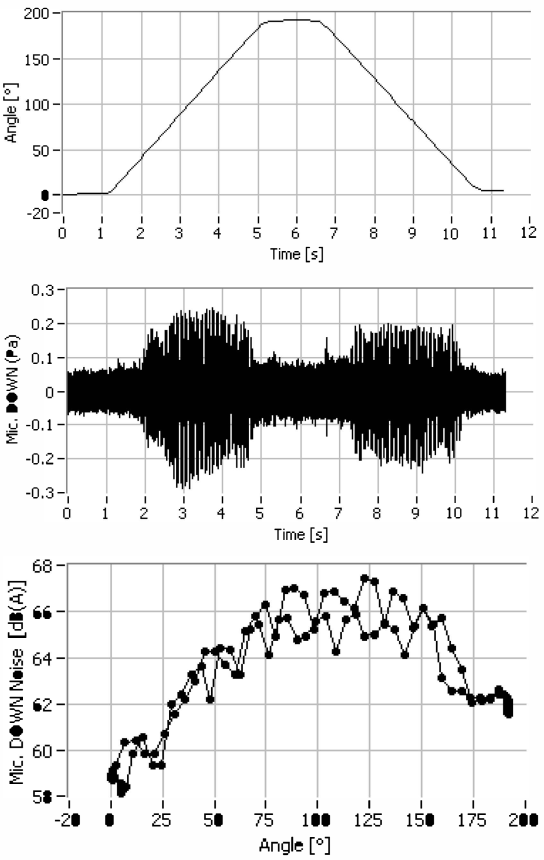

Fig. 2. The angle and the brushes microphone (Mic. DOWN) time histories and the noise level in dB (A) plotted vs the angular position of motor #0070.

A peak-hold averaging has been done in order to keep only maximum and minimum value of each feature. That's because it is not necessary that a motor is noisy in all the positions, when it is perceived as noisy in just one position the operators usually discard it.

Features have been normalized using a standard score method, i.e. subtracting from each value the average of the training sample and dividing each one for the standard deviation. Normalized features have been linearly combined in order to obtain a "damage score" and a ranking that has been correlated with classification made by operators. The weighting factors have been suggested by the motor producer, according to their experience and following the relation (1) specified below the noise levels have more importance with respect to the vibrations and electrical characteristics.

$$D = M_u + M_d + 0.6 \cdot A + 0.4 \cdot C_{DC} + 0.3 \cdot C_{AC} + 0.5 \cdot RPM \qquad (1)$$

D is the damage score, M_u and M_d are Mic.UP and Mic.DOWN noise, A is the acceleration, C_{DC} and C_{AC} are DC and AC current and RPM is the rotational velocity of the motor.

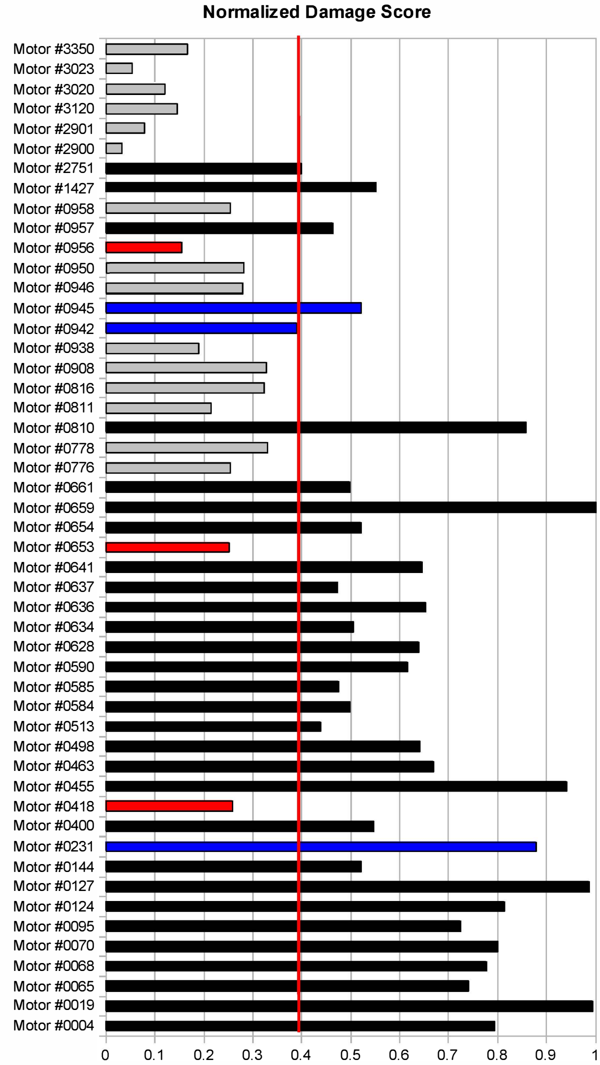

Fig. 3. Synthetic results of the experiment and threshold imposed.

III. RESULTS

Figure 2 reports the angular position and the brush microphone (Mic. DOWN) time histories, together with the noise level in dB (A) plotted versus the angular position of motor #0070 that exhibit the typical behavior of a faulty motor. Stating from 0° position (vertical), when the angle is around 90° (horizontal), the noise produced increases from 58 to 67 dB(A).

Figure 3 shows synthetic results of the experiment. In the bar plot each measured motor is represented by its serial number and damage score obtained in the experiment. The red vertical line is the threshold between good and faulty motors: if the damage score goes over the threshold, the motor is considered faulty. Black bars represent motors that exceed the threshold and are also judged faulty by operators, grey bars are motors that do not exceed the damage index threshold and are also judged good by operators, blue bars are motors that exceed the damage index threshold but are judged good by operators, and red bars are motors that do not exceed the damage index threshold but are judged faulty by operators.

In 44 cases on a total of 50 motors tested, the results of the test overlap the judgment made by expert operators.

IV. DISCUSSION

The not perfect overlapping of the results of the test bench with the classification made by operators is probably due to the small sample used to train the system and to the large variability in electrical and mechanical characteristics that this kind of motor can have even if they all are of the same model.

Using a supply voltage of 3 Vdc, the absorbed DC current can vary from 1.2 to 1.5 A. Rotation velocity also varies between 890 and 1130 RPM. As shown in Figure 4, over 1.6 A the rotational speed is negatively correlated with the absorbed current.

When the rotational speed is lower, the noise perceived by the operator is lower too, so the motor is classified as good even if it is faulty from power absorption and RPM point of view. It is clear that if the RPM is too low, the HVAC system where that motor will be mounted would probably not satisfy requirements in terms of efficiency and air flow rate, so the motor has to be considered faulty.

Motor #0942 has a DC current absorption of 2.4A, almost double of the average of good motors that is around 1.3A. Velocity is low too, 900 RPM while the average of good motors is 1050. From noise and vibration point of view it is "normal", so the operators judged it good but in the proposed test, having a very bad performance in current absorption, the damage score of 0.39 makes it classified as faulty.

For motor #0945 the mismatch in the results is probably due to its time history pattern. As shown in Figure 5, faulty motors time histories are in most of cases modulated by peaks that occurs at the rotational speed frequency or at its multiples [10, 11], while motor #0945 has a relatively high level, but homogeneously distributed in amplitude. Operators are used to recognize this kind of "ticking sounds", as the modulation of noise is easier to recognize than a high absolute level [12]. This explains why operator classified this motor as good even if the overall noise produced is high.

Motor #0293 behavior is even different: observing plots in Figure 6, during the rotation the noise level remains almost constant, while vibration level and current absorption increase significantly over 160°, i.e. when the motor is upside down.

These types of defects are due to the high friction between rotor and stator that occurs only in certain specific motor orientation in the space. It is very difficult for the operator to individuate them, as they do not produce any change in noise, but only an increment of vibration level, that the operator should recognize just holding the motor in the hand.

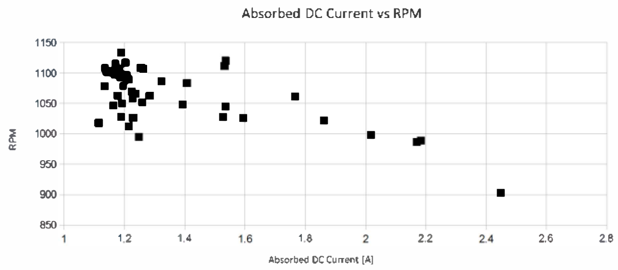

Fig. 4. Absorbed current versus motor's shaft RPM, after 1.5A it is negatively correlated with RPM

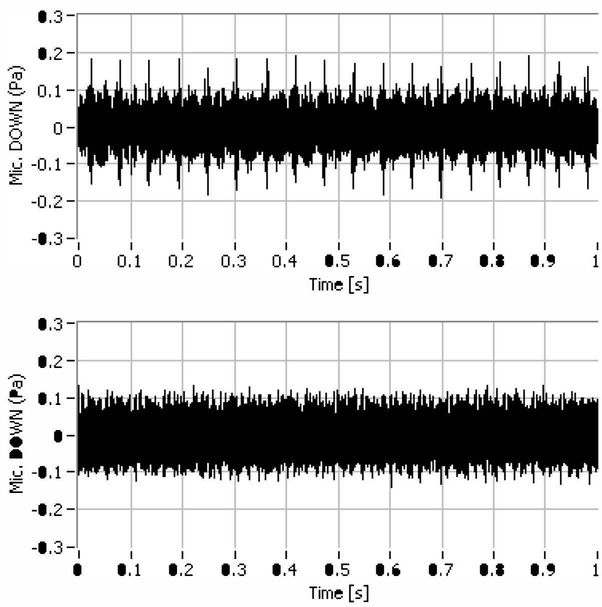

Fig.5. Comparison between time two histories recorded by the brushes microphone (Mic. DOWN). Above a typical faulty motor (#0068), below motor #0231 considered a good motor.

V. CONCLUSIONS

In this paper, problems related to noise and vibration testing of small permanent magnets DC motors in production line have been reported and discussed.

According to the usual production line testing procedures and to suggestions of a well know DC motors manufacturer, a prototype of a semi-automatic test bench has been constructed and used to collect current, noise and vibration data on a small sample of good and faulty motors.

Different signal processing techniques found in literature [6, 10, 11, 13, 14] have been evaluated, but as the first objective of this campaign of test is to reproduce the results of expert operators classification, quantities related to human perception of noise and vibration like dB(A) - weighing [7] and W(h) - weighting [8] have been used.

For a complete characterization of the motor, features extracted from mechanical measurements have been integrated with electrical ones, like AC/DC current and voltage.

A damage score has been calculated from a linear combination of all the measured features, and results show that it is well correlated with the classification made by expert operators.

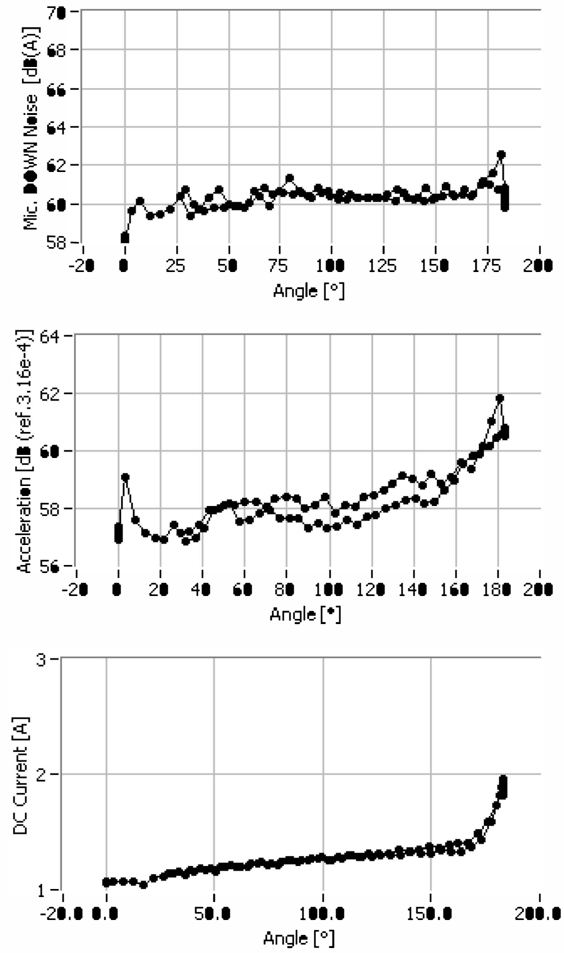

Fig.6. From top, brushes noise (Mic. DOWN), acceleration and absorbed DC current of motor #0293 plotted versus angular position.

Discrepancies between results are explicable when samples that are good for the operator and faulty for the automatic test, while it's still not clear why 3 samples on a population of 50 pass the automatic test but are judged faulty by operators.

At present the system has been trained to reproduce the classification made by operators in a global judgment of the motor noise and vibration performances, but other tests on a bigger sample have already been planned to train the system to distinguish among different kind of defects.

Furthermore, additional tests are now ongoing in order to check repeatability of test performed by different operators, to collect more information on the type of defect they can recognize in faulty motors and to evaluate the repeatability of the results produced by the proposed test system in severe background noise conditions that can occur close to a production line. The final results will be used to the design a fully automatic test station to be placed in production line to perform quality control on 100% of production.

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