Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
 Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26231-cd

Influence of brake shocks on safety components of electric motors

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Brake shocks, which occur on electric motors when the brake is applied, have a damaging effect on the immediate surrounding components. Safety-relevant rotary encoders, used to detect angular position and speed, are particularly affected. The influence of brake shocks can be either reversible, in the form of temporary signal distortion, or lead to permanent mechanical damage. In the past, these types of shocks were insufficiently considered in the standardization of tests. Shock tests for encoders were specified only with half-sine excitation, whereas real brake shocks are high-frequency, transient events. In 2021, a draft of the IEC 61800-5-3 standard was published, proposing an extended shock-testing procedure that considers the characteristics of real brake shocks. Based on this testing procedure, this publication presents extensive lifetime tests on safety encoders and their results, including a simplified qualification procedure.
First, the pseudo-velocity shock response spectrum, used to describe brake shocks, is introduced. After that, the testing procedure is explained, and an overview of the parameterization of the developed testing machine is given. It was observed that brake shocks cause both reversible impairments and irreversible damage to safety encoders. A wide variability of failure times and damage patterns was observed. The results of the endurance tests were statistically evaluated using Weibull analysis. Additional evaluation was carried out using the Weibayes approach because the testing procedure is time-consuming and the available basic population for statistical evaluation may be small. Finally, a newly developed shock measurement system is presented, suitable for practical brake shock measurements on the motor shaft. Additionally, a qualification procedure for safety-relevant encoders is introduced, based on a proven-in-use approach. This procedure offers a simple solution to fulfill the requirements of the new draft of IEC 61800-5-3.

Keywords: Brake shocks, Reliability, Encoders, Electric motors.

1. Introduction

Brake shocks are transient, oscillatory shock pulses. They can have a reversible effect on safety-related components in electric motors or cause irreversible damage. (Rieger and Hagemann 2017) Until now, this type of shock has not been given sufficient consideration in the standardization of encoder tests.

This publication provides a brief introduction to the origin and evaluation of brake shocks. It then describes endurance tests that were performed on rotary encoders using a test bench. The failure mechanisms and failure times are presented and statistically evaluated. Weibull analysis, which is mainly used for failure data, is employed for this purpose. This analysis is supplemented by the Weibayes approach to obtain a further statistical assessment suitable for a small number of samples. The final section presents a measurement system that can record acceleration data from brake shocks directly at the shaft of electric motors and transmit it wirelessly. It offers the possibility of qualifying rotary encoders using a proven-in-use approach.

2. Mathematical Description and Evaluation of Brake Shocks

Brake shocks exhibit high positive and negative accelerations and span a frequency range of several tens of thousands of hertz. (Rieger and Hagemann 2017) Their average duration is between ten and fifteen milliseconds, see Fig. 1. (Rieger and Hagemann 2017)

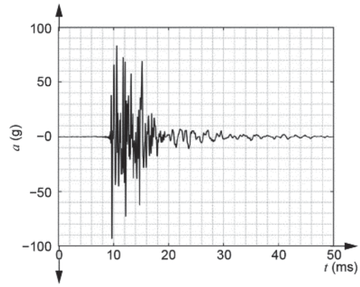

Fig.1. real brake shock (IEC 61800-5-3:2021)

2.1. *Origin and characteristics of brake shock*

Brake shocks occur when the brake at the electric motor is applied and released, and spread through various paths in the motor environment. (Rieger and Hagemann 2017) These shocks can vary in intensity and therefore have varying potential for damage. The severity of the shock depends on the brake characteristics, such as the braking force, and on the motor shaft's rotational speed. This means that different motor-brake configurations have different potentials for damage. (Rieger and Hagemann 2017)

2.1. *PVSRS and interpretation of the shock severity*

The severity of brake shocks cannot be directly evaluated from the acceleration-time curves. For this reason, pyro shocks were previously assessed using the pseudo-velocity shock response spectrum (PVSRS). Since brake shocks are similar to pyro shocks, it is appropriate to evaluate brake shocks using the PVSRS as well. (Rieger and Hagemann 2017)

The PVSRS is calculated using the same basic procedure as for the shock response spectrum (SRS). A mathematical model with single-degree-of-freedom (SDOF) oscillators is excited with an acceleration signal, and the different natural frequencies of the SDOF model result in different maximum displacements in the oscillators' response. (European Cooperation for Space Standardization (ECSS 2015)) This is used to form the Maximax-SRS. (ECSS 2015) For the PVSRS, either the acceleration signal is first integrated and used to excite the SDOF model (ECSS 2015), or the Maximum-SRS is calculated first and then integrated to obtain the PVSRS. (ISO 18431-4:2007) Finally, the PVSRS can be plotted on four-coordinate paper (4CP). The parameters pseudo-velocity, frequency, deflection, and acceleration are plotted. The PVSRS usually shows a plateau within a specific frequency range, see Fig. 2. (Rieger and Hagemann 2017)

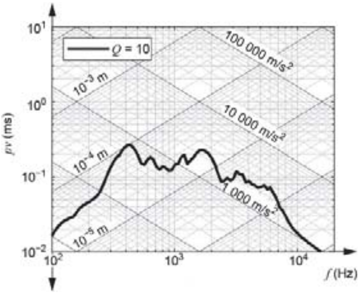

Fig.2. Pseudo-Velocity Shock Response Spectrum (IEC 61800-5-3:2021)

This plateau can be used to determine the potential damage caused by the braking shock. (Gaberson 2007) The higher and wider the plateau, the greater the severity of the shock. (Gaberson 2012) Since the PVSRS calculation depends on the response of the SDOF model, different acceleration-time curves can have the same PVSRS. (Napp 2026)

3. Endurance Tests with Rotary Encoders

Until now, little attention has been paid to the phenomenon of brake shocks and their influence on rotary encoders. This is reflected in the shock test procedure that was mandatory until 2021. Rotary encoders must be tested with a half-sine wave of amplitude 5 g and a shock duration of 30 ms. (IEC 61800-5-2:2017) This testing procedure does not reflect the real characteristics of brake shocks. Therefore, the draft of IEC 61800-5-3 presents a shock test procedure in the informative section, using an appropriate test bench to test rotary encoders with realistic shock characteristics. (IEC 61800-5-3:2021 appendix D) Since no realistic results are known from previous shock tests, endurance tests and their results are presented below, in which realistic brake shock characteristics were simulated for the testing procedure.

3.1. *The testing machine*

The used testing machine corresponds to the setup described in IEC 61800-5-3 under the extended shock test (Fig. 3).

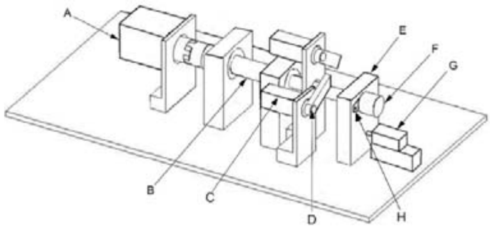

Fig. 3. Testing machine (based on IEC 61800-5-3)

To simulate brake shocks, three mallets are accelerated in succession by electric motors and strike the central shaft of the test bench (B) or the stator plate (H). This type of shock simulation enables the creation of shocks very similar to real brake shocks and subjects the tested components to many shocks in a short period of time (approx. 25 shocks per second). As shown in Fig. 3, the rotor of the tested devices under test (DUTs) is mounted on the central shaft, and the stator of the DUT is connected to the stator plate of the test bench via a rigid connection.

3.2. *Tested specimen*

The DUTs tested in this research project are rotary encoders that detect the position and speed of the motor shaft. This information can be used to monitor and adjust the motor control. (Napp 2026) If the rotary encoders fail, the motor control cannot be executed correctly, which can result in hazards to people and the environment, as well as availability restrictions. During the endurance tests, optical rotary encoders with a self-supporting bearing were tested. In addition, the test specimens were capable of both detecting the absolute position and the number of revolutions. This type of rotary encoder is called an absolute multiturn rotary encoder. Many encoders are equipped with a stator coupling. This is designed to compensate for the motor shaft's radial and axial displacement and prevent the encoder stator from rotating. The tested encoder type has a so-called torque support as a stator coupling. This is mounted on the stator plate of the test bench with screws.

3.3. *Test procedure*

For the endurance tests, the test bench was parameterized to simulate realistic brake shocks (Fig. 4).

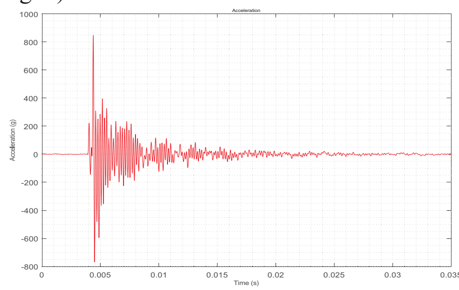

Fig. 4. Replicated brake shock

Before each test, each test specimen underwent a preliminary examination. This included a visual inspection under a microscope and a check of the sensor signals. The initial examination was intended to ensure that any pre-existing damage was documented.

The endurance tests were divided into intervals of 100,000 shock cycles. After each test interval, the test specimen underwent visual inspection. The sensor was examined for external damage, and it was checked whether the test specimen was still correctly mounted. If the interim test was unremarkable, the next test interval was started. As soon as damage was observed, the endurance test was terminated. If no damage was observed, the endurance test continued until 5 million shock cycles were reached.

Once the endurance test was completed, the test specimen underwent a follow-up inspection. This included the same tests as the preliminary inspection and a functional test. The aim was to ensure that any internal damage affecting the encoder signals was detected.

4. Results and Statistical Analysis

It was observed that brake shocks have a reversible effect by causing signal interference. In addition, irreversible damage can occur, as discussed below. To date, 15 encoders of the same type have undergone endurance testing, and nine test specimens have failed.

The failure mechanisms vary widely, and only one type has been observed twice. In addition, the failure times exhibit considerable variation. First, an overview of the failures is provided, followed by a statistical evaluation of the interval-censored data.

4.1. *Observed failure mechanisms*

Table 1 provides an overview of the failed test specimens. It shows the number of shock cycles after which the test specimens failed and lists the failure mechanisms observed in each case. Test specimens that survived the endurance tests without damage are not included in the table.

Table 1. Overview of failure times and damage patterns

No.	failure time (mio. cycles)	Failure mechanism
1	2.1	Failure of the adhesive bond between the housing and the bearing
3	0.9	Breaking the electrical interface from the circuit board
3	2.8	Unilateral fracture of the DMS
7	1.9	axial movement; internal failure (comparative test)
8	1.4	internal failure (Multiturn position error)
9	0.6	internal failure (Multiturn position error; incorrect angle offset)
10	3.97	axial movement; internal failure (comparative test)
12	0.5	Threaded pin broke off from the sensor cone
13	2.0	Threaded pin broke off from the sensor cone
15	0.3	internal failure (Multiturn position failure; I^2C not operational)

Fig. 5 shows the (unilateral) broken torque support. A broken torque support can cause the internal sensors to shift relative to one another, increasing stress on the torque support. (Schepers and Schwarzer 2023) Correct motor control is no longer possible if the sensors shift, but this can usually be detected by overcurrent detection before the torque support breaks completely.

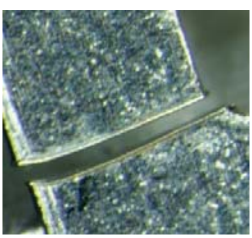

Fig. 5. Broken torque support (Schepers and Schwarzer 2023)

Fig. 6 shows a broken threaded pin. This failure mechanism occurred at the same breakpoint in two test specimens (Fig. 7). This failure resulted in falsified sensor signals, rendering correct motor control impossible.

Fig. 6. Broken threaded pin (Napp 2026)

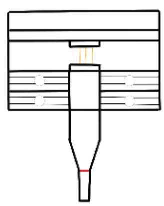

Fig. 7. Schematic localization of the fracture site (red) (based on Napp 2026)

4.2. *Weibull analysis*

First, the failure data is evaluated using the Weibull distribution. This distribution is widely used in the evaluation of lifetime data. The result of this evaluation is, on the one hand, the characteristic lifetime T and, on the other hand, the shape parameter b, which provides information about the type of failures that have occurred. A distinction is made between early failures, random failures, and fatigue/wear failures. The data was evaluated using the Visual XSel tool and verified using the Releyence tool.

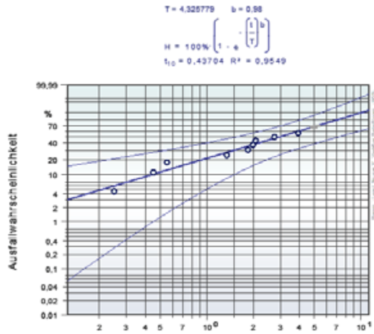

Fig. 8. Visualization of results of Weibull-Analysis (Napp 2026)

A value of approximately 4.32 million shock cycles was determined for *T,* and approximately 0.98 for *b* (Fig. 8). The shape parameter indicates that the failures fall into the early-failure category. However, since fatigue failures must be considered plausible, the result indicates that the sample size is insufficient for statistical evaluation. For this reason, the following section presents and applies a method that is suitable for samples with very few failures.

4.3. *Weibayes analysis*

One approach to the statistical evaluation of lifetime data that can be applied to samples with no or very few failures is Weibayes analysis. (Abernethy 2004) For this method, the shape parameter *b* must be available as prior information. This value can be derived from expert estimates or similar analyses. The shape parameter is linked to the failure data as a conditional probability, so that this approach can be considered a single-parameter Weibull analysis. (Abernethy 2004) Here, the characteristic lifetime is estimated using maximum likelihood. Based on the data in Table 1, the range of the minimum characteristic lifetime T_{min} was 4.772 to 4.965 million shock cycles. This range depends on which *b* was assumed as prior information. The analysis was performed using the upper and lower limits of the confidence interval for *b* determined in the previous Weibull analysis. This range indicates that the assumed shape parameter introduces a degree of uncertainty into the results, so it is advisable to generate a larger sample to obtain more reliable results from the Weibull analysis.

5. Simplified Test Procedure for Encoder Qualification

Since the endurance tests described are both costly and time-consuming, a newly developed measuring system (SCHIRTE) for recording brake shocks directly on the shaft of real brake motors is presented here. Subsequently, an approach for qualifying rotary encoders is described that uses the presented measuring system.

5.1. *Description of the wireless measurement system*

The developed measurement system generally consists of a circuit board for data acquisition and processing, data transmission components, and a power supply unit. All these units are housed in a casing that allows the system to be mounted on a motor shaft. A triaxial MEMS acceleration sensor with a measuring range of ±2000 g and a cut-off frequency of 10 kHz is used for data acquisition. Data processing is performed by a microcontroller, from which the data is transferred to a connected computer. A particular feature of the measuring system is that it transmits data wirelessly via Bluetooth. This allows it to be used directly on the rotating shaft of an electric motor. This makes it possible to record real brake shocks to evaluate the damaging potential of the specific motor-brake configuration. The triaxial acceleration sensor enables recording of brake shocks along different axes. In the current implementation, the x and z axes are recorded. A switch can be used to set whether the axes are recorded sequentially at approximately 97 kHz or in parallel at a reduced sampling rate. Power is supplied by a LiPo battery, which can be charged via Micro-USB. The system is programmed via an UPDI interface, which allows for adjusting the trigger level. This is necessary because the measurement system automatically records the acceleration data if the programmed trigger level is exceeded. Once the trigger level has been detected, the measurement system records approximately 17 ms before the trigger and approximately 43 ms after the trigger, resulting in a total recording time of 60 ms. The recorded data is received on the connected computer via a terminal program and must be further processed in a suitable program to visualize the data and calculate the PVSRS.

5.2. *Validation of the measurement system*

The initial version of the developed measurement system has already been validated. First, on a shaker, the recorded data corresponded well with those from an alternative wired sensor (Fig. 9).

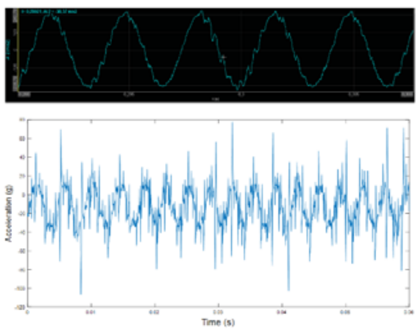

Fig. 9. Comparison of recorded data between the measuring system and the wired sensor (Napp 2026)

The measuring system was then mounted on a brake motor to record real brake shocks (Fig. 10). Comparing the figure below with Fig. 1, it can be seen that the measuring system adequately records brake shocks.

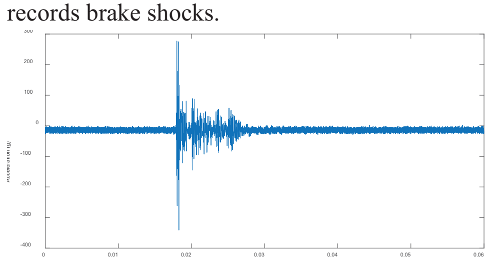

Fig. 8. Brake shock at 800 rpm (Napp 2026)

Nevertheless, the illustrations in Figs. 9 and 10 show that high noise levels persist in the first version of the measuring system. A revised version designed to reduce noise influence significantly is currently being finalized.

5.3. *Data evaluation and proven-in-use approach*

The measurement system presented above is intended to give manufacturers of electric motors and rotary encoders a better understanding of the service life of rotary encoders under the stress of brake shocks. (Napp, 2026)

Since the damaging effects of brake shocks can vary significantly across different motor-brake configurations, it is advantageous to use rotary encoders based on their load capacity. The measuring system can be used in various ways for this qualification.

First, the measurement system can be used to identify the motor-brake configuration in the manufacturer's product portfolio that causes the most damage. To do this, the configuration data recorded by the measurement system must be converted into a PVSRS using suitable software so that the damage caused by the different configurations can be compared. With this information, the measurement system can be used to parameterize a test bench (Fig. 3) so that the brake shocks of the identified configuration can be simulated. Various rotary encoders can then be tested on this test bench to determine their service life. Rotary encoders that survive these endurance tests without damage can be used in all other configurations without expecting failures due to fatigue.

Alternatively, rotary encoders can be qualified based on field applications using a proven-in-use approach. To do this, the past failures of the motor-brake configuration that have had the most significant damaging effect are considered. It is essential to determine whether failures have occurred and, if so, how often. If no failures attributable to brake shocks have been observed, the applied rotary encoders can be employed in all configurations. If failures due to brake shocks have occurred, either the affected encoder type must be designed to be more robust, or an encoder type must be used in this configuration that is appropriately designed for the occurring shocks. The proposed qualification methods are independent of the encoder technology, as any encoder for electric motors can be observed in the field and tested on a test machine. With the help of the described measurement system, the shock loads can be determined realistically and wirelessly, enabling a worst-case estimation of the motor-brake configurations and the parameterization of a testing machine.

6. Summary and Conclusion

Brake shocks can have a reversible or irreversible damaging effect on safety components in electric motors. Following a brief introduction to brake shocks, their causes, and the assessment of their harmful effects, various failure mechanisms in rotary encoders were demonstrated in endurance tests. These failures can affect the safety and availability of applications with electric motors. For example, a collaborative robot whose electric motor lacks proper control can injure a person performing tasks alongside the robot. In addition to the failure mechanisms, the endurance tests also recorded service life data, which were evaluated using the Weibull method. Since the small sample size contains only a few failures, the Weibayes approach was also applied to the available data. Both evaluations yielded similar results for the characteristic service life. Nevertheless, the sample size should be increased in future investigations to obtain more meaningful results.

A measurement system was presented that, thanks to its wireless data transmission, is suitable for recording brake shocks under real conditions. It was validated using tests on a shaker and a brake motor. In a final step, it was described how the measurement system can be used to qualify rotary encoders under the stress of brake shocks.

This publication aims to make this measurement system available to the general public, thereby contributing to improved understanding of brake shocks and facilitating the qualification of rotary encoders. The necessary plans for replication of the PCBs and the program code are available at:

https://github.com/NappSchepers/Brakeshocks

A program for visualizing shock data and calculating the PVSRS using the open-source tool Octave is currently under development. Therefore, a complete open-source solution for measuring and evaluating brake shocks will soon be available to developers and users of electric brake motors.

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