OUTRIGHT DETECTION OF DRIVE ROD TO DIAPHRAGM ASSEMBLY-LEVEL RELIABILITY FAILURES

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ABSTRACT

A good manufacturing process aims for consistent quality and product performance. It continuously endeavors to obtain a proper set of controls and sufficient detection points to capture failures at an earlier stage, thus reducing scrap costs, rework, reliability issues, and, most importantly, customer complaints.

This paper discusses the development of a test method to measure the strength of the drive rod to diaphragm connection at an assembly level - both critical components of a balanced armature (BA) driver. Statistical process control (SPC) is then used in the performance monitoring, out-of-control detection, and immediate correction of the special causes of these variations. This early detection test method in turn reduces the burden of relying on lagging indicators such as Ongoing Reliability Tests (ORT) to identify any possible failures. This test method was also used to characterize and improve the performance of a critical component of the BA driver to further reduce the risk of ORT failures.

1.0 INTRODUCTION

Balanced Armature (BA) drivers are transducers that use the principle of electromagnetism (electromagnetic induction) to convert audio signals (electrical energy) into sound waves (mechanical wave energy).

A BA driver uses an electronic signal to cause a varying magnetic field in the coil to vibrate a tiny reed (armature) that is balanced between two magnets inside a tiny enclosure (thus the term balanced armature). The motion of the reed is transferred to a very stiff aluminum diaphragm through a drive rod which acts as a mechanical coupler. This diaphragm then produces the sound waves the user hears. BA drivers are also called BA receivers. A cross-section of a BA driver and its typical designated usage is illustrated in Figure 1.

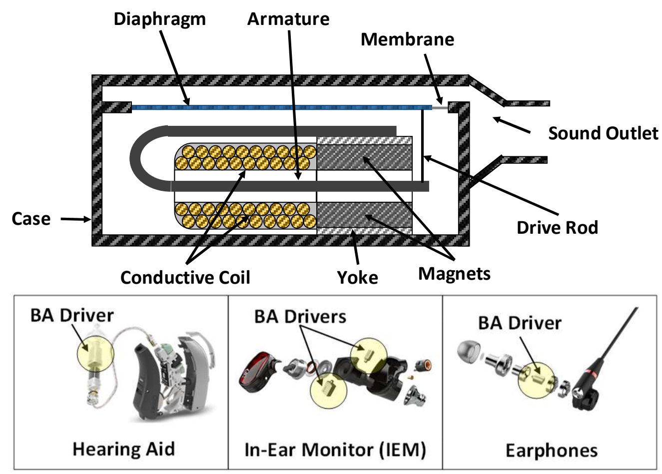


Figure 1. Cross-section of a Balanced Armature Driver and its typical designated usage.

BA drivers are one of if not the most critical components in hearing aids, In-ear monitors, and earphones. It is imperative that all parts of a BA driver are free of defects to function properly and according to its desired specification.

A typical failure of a BA driver is a decoupling of the connection of the drive rod to the diaphragm. As illustrated in Figure 2, a decoupled drive rod from the diaphragm only produces sound when the BA driver is negatively biased (the drive rod moves up). A BA driver does not produce an equivalent sound pressure when positively biased as the diaphragm is no longer connected to the drive rod when the reed moves down. This renders the BA driver incapable of producing desirable sound output. The graph shows this as an increase (negative bias) and decrease (positive bias) in Sound Pressure Level (SPL) with units in decibels (dB).

This failure mode is usually detected after conducting a series of Ongoing Reliability Tests (ORT) on the BA drivers.

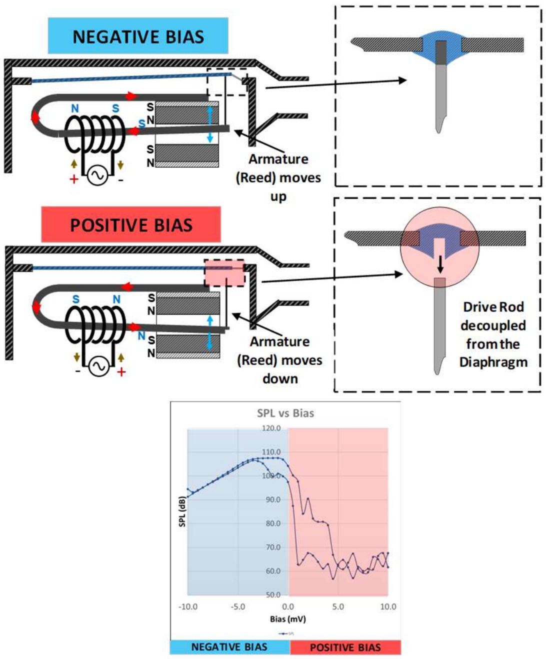


Figure 2. Sound Pressure Level vs. Voltage Bias of a Balanced Armature Driver with a mechanically de-coupled Drive Rod to Diaphragm connection.

In this paper, a development of a test method was considered to detect this failure mode at an assembly level, or when the BA driver is in ongoing production, which is an immediate detection method and earlier than what was previously established. This test method was also used to characterize the current mechanical coupling performance and to optimize the overall assembly and product quality of the BA driver.

2.0 REVIEW OF RELATED WORK

Not applicable

3.0 METHODOLOGY

In this paper, the team delved into the application of the PDCA cycle and utilize its key principles to develop and establish the appropriate optimized test method that aligned with the objectives of the project.

3.1 PDCA – Plan Phase

3.1.1 Review of Reliability Test Failures

A certain BA named Model "X" experienced several units failing the Ongoing Reliability Tests (ORTs). The specific ORTs that the BAs from this model were exposed to and failed are: Highly Accelerated Life Test (HALT) and mV Drive Level Stress Test. These specific tests are to simulate the BA drivers' possible exposure to certain environmental conditions in the field. The BAs that were exposed to these ORTs experienced higher levels of mechanical and environmental stress in comparison to normal conditions. (See Table 1 for each ORT specific test condition.)

Table 1. ORT and Equivalent Test Condition

Item	ORT	Condition
1	HALT	BA is continuously driven at voltages higher than the nominal voltage drive level while being exposed to elevated levels of temperature and % relative humidity for 6weeks
2	mV Drive level Stress T	BA is continuously driven at elevated voltages (twice the voltage setting of HALT in terms of dB) for 1Hour

3.1.2 Reliability Test Failure Analysis

BAs from Model "X" that failed after exposure to these ORTs were analyzed. Figure 3 is an illustration of the common failure mechanisms observed upon examining the failed BAs. The drive rods of these BAs have been decoupled from the diaphragms. The decoupling is in such a way that the drive rod is always detached from the cement adhesive, which acts as the mechanical coupler to the diaphragm. The cement adhesive always remains in the diaphragm and does not accompany the decoupled drive rod.

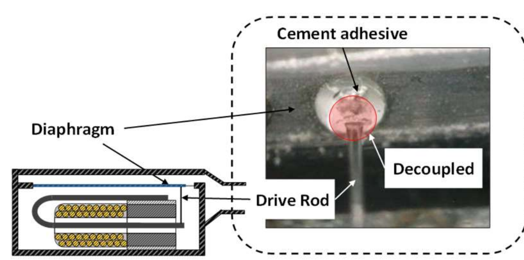


Figure 3. Actual image of the representative BA that failed the ORTs.

3.1.3 Failure Mechanism and Review of Equivalent Process Detection Points

Based on the process block diagram of Model "X", which is shown in Figure 4, the final process that determines the assembly quality of the drive rod to diaphragm coupling is the drive rod cement adhesive application process. Detection points for Quality related failure mechanisms are during Visual Inspection, Acoustic Test, and Outgoing Quality Inspection process. Failures identified from the ORTs however are Reliability in nature, wherein these units only fail if subjected to higher levels of mechanical stress. These failures were captured only at the ORTs.

As an improvement, an additional detection point at the assembly level (post-drive rod cement adhesive application process) will have to be implemented.

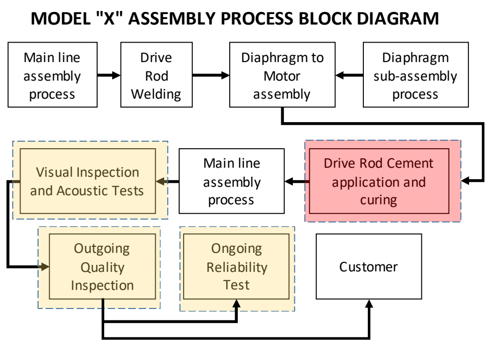


Figure 4. Model “X” Assembly Process Block Diagram.

3.1.4 Drive Rod to Diaphragm Mechanical Coupling Design Analysis

The design of the drive rod to diaphragm coupling involves a cement adhesive acting as a mechanical coupler between two components. Figure 5 is an illustration of the close-up view of the BA driver cross-section of this mechanical connection.

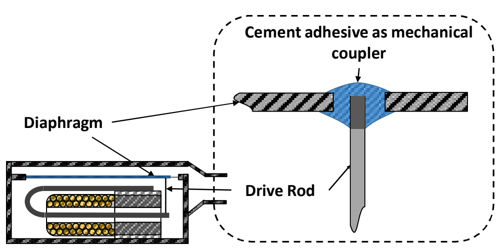


Figure 5. Extreme close-up view of the drive rod to diaphragm connection.

From a product quality perspective, critical characteristics are the cement adhesive cured properties, while from a process quality perspective, certain variabilities determine the overall reliability of this connection. Figure 6 identifies two major variations that are determined by the process, and critical to the drive rod to diaphragm connection. These are the drive rod height and cement adhesive volume. A higher drive rod given a nominal cement adhesive volume will result in a larger cement adhesive coverage on the drive rod compared to a lower drive rod given the same nominal cement adhesive volume. Likewise, given the same drive rod height, a larger cement adhesive volume will result in a higher cement adhesive coverage on the drive rod compared to a lesser cement adhesive volume.

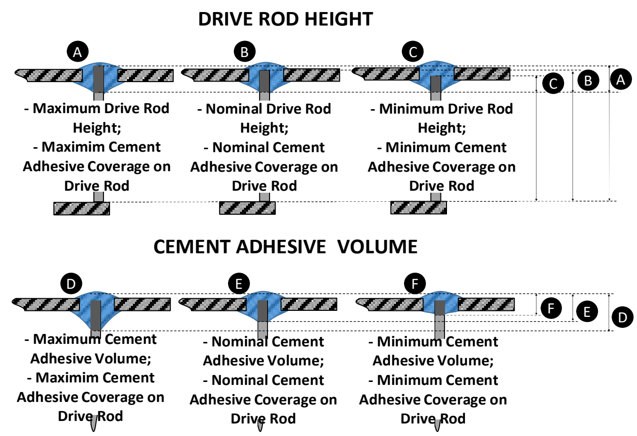


Figure 6. Drive rod cement adhesive coverage variability.

3.1.5 Drive Rod Pull-Out Test Analysis

Both the drive rod height and cement adhesive volume are separately controlled parameters in the assembly process. It is the product of the interaction of both parameters in the assembly process that the team intended to control that led to the development of a Pull-Out Test specific to the drive rod to diaphragm connection which is a breakthrough in Knowles BA assembly process, and was never before done on any product before Model “X”.

With the result of the analysis of the drive rod to diaphragm connection and the identified variables, it was determined that the ideal test to be performed at the assembly level is the pull-out test of the drive rod from the drive rod cement adhesive. The characteristic to be measured is the Force needed to break the drive rod from the cement adhesive. The formula is defined as:

$$\tau = \frac{F}{A};\ F = \tau A$$

Where τ is the shear strength, F is the force applied to break (force at failure), and A is the cross-sectional area of material parallel to the force (force resisting area).

$$A = A_L;\ A_L = 2\pi rh$$

Where A is equivalent to A_L, the area of the lateral surface of a cylinder, h is the height of the cylinder. The lateral surface area of the cylinder is used as this is the area that is sheared from the cement adhesive.

$$F = \tau 2\pi r h;\ F = \tau 2\pi \left(\frac{D}{2}\right) h$$

Therefore, F will be determined, where F is the force applied to break, τ is the shear strength, D is the diameter of the drive rod, and h is the height of the drive rod that is covered by the cement adhesive.

The Force applied to break F is directly proportional to h, where theoretically, as h increases, F also increases. D is the diameter of the drive rod, considered a constant (0.0483mm). τ is the cement adhesive compression shear strength (30MPa converted to 2855gf/mm²). τ is also considered a constant. See Figure 7.

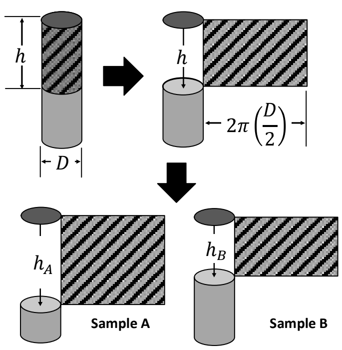


Figure 7. Extreme close-up view of the drive rod.

Table 2 contains sample calculations of the Force to break in gf. Both the D and τ constants would only have expected changes if there are special causes contributed by the drive rod diameter, cement adhesive curing condition, or the cement adhesive formulation. Control of the drive rod diameter is being performed by the incoming quality inspection, while the cement adhesive is an off-the-shelf component with material declarations as a reference for any formulation changes. Cement adhesive curing parameters on the other hand are being controlled separately through machine daily parameter checks.

Table 2. Sample Calculations

Sample	*height* (mm)	*Diameter* (mm)	τ (gf/mm2)	*Force* (gf)
A	0.7000	0.0483	2855	303.02
B	0.5000	0.0483	2855	216.44

3.2 PDCA – Do Phase

3.2.1 Test Method Conceptualization and Development

The test method conceptualization and development has been done from the sample preparation, equipment identification, fixture design, up to the test procedure. The team acknowledged the challenge of doing mechanical testing on components with less than hundreds of microns in size.

3.2.1.1 Sample Preparation

A major challenge that the team has encountered was specific to how the BA driver has to be disassembled to retrieve only both the drive rod and diaphragm undamaged and with the drive rod still attached intact to the diaphragm. A disassembly method has to be generated to achieve this objective. Based on the process flow block diagram, it can be observed that the drive rod cement adhesive application process is already in the middle of the BA driver assembly process, which means, most of the components of the BA driver are already attached to the unit. See Figure 8 on the sample preparation and disassembly process illustration.

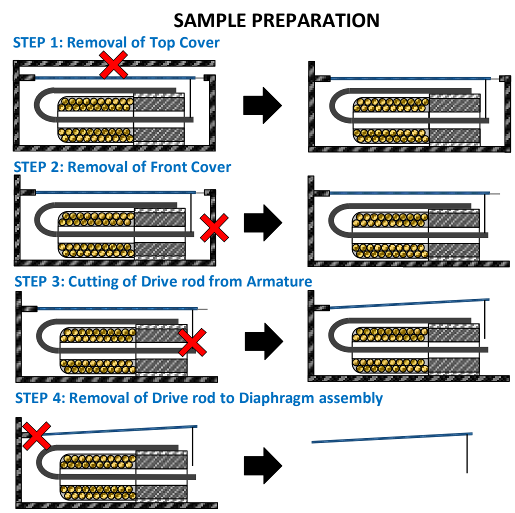


Figure 8. Sample preparation and disassembly process.

3.2.1.2 Equipment Identification

The team has identified to use a spare compact semi-automated 3-axis desktop robot previously used as a dispenser. This was the equipment of choice as it was readily available and will entail no cost. It has constant speed, is versatile, programmable, and has repeatable results. See Figure 9 for a sample image of the equipment.

Figure 9. Equipment – 3-axis desktop robot.

3.2.1.3 Fixture Design and Test Method

An equivalent fixture and nest as illustrated in Figure 10 were designed from scratch to accommodate the diaphragm and drive rod assembly for testing. The nest is to contain the diaphragm, while a gripper on the opposite side is clamping on the tip of the drive rod. The gripper remains on a fixed position while the nest pulls in the opposite direction being connected to a 500g tension load cell. The pull is controlled by the robot arm and is conducted at a constant 20mm/ minute pull speed. This speed is standard across all Knowles mechanical tests. The peak Force to break (F) the drive rod is pulled from the cement adhesive is then displayed in Newtons (N). Newtons is used so as to align with the common test parameters at the assembly process using the same unit of measurement.

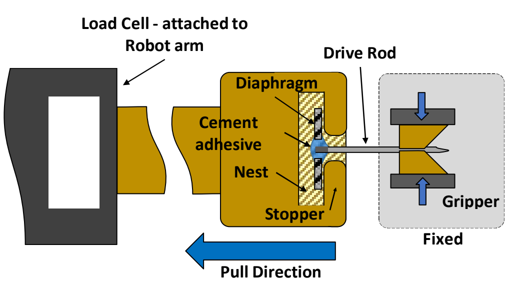
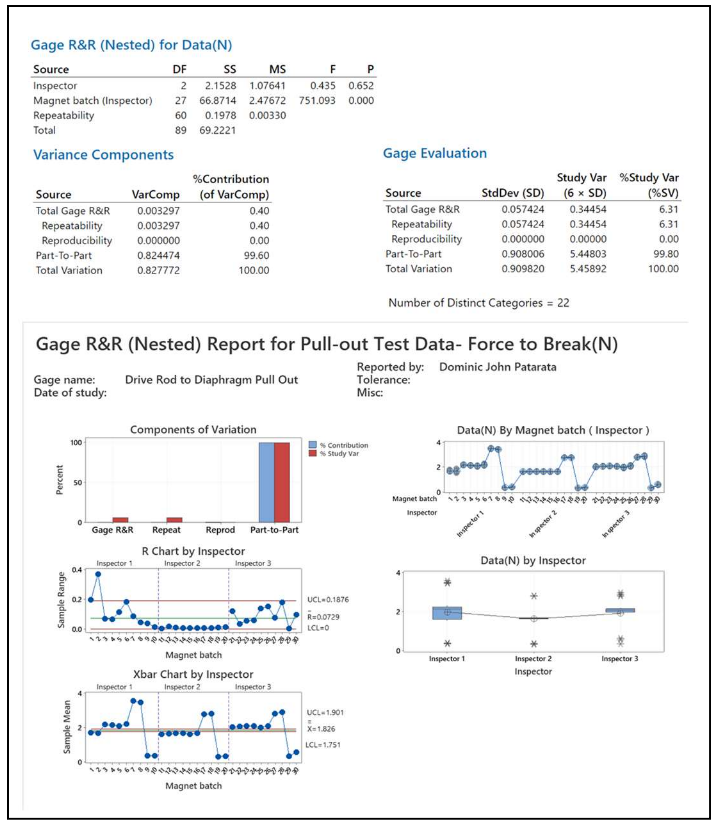


Figure 10. Test Fixture Design and Mechanism.

3.2.2 Test Method and Set-up Qualification

Qualification has to be done on the Pull-out Test Set-up and Method before it has to be implemented. A Nested Gage Repeatability and Reproducibility (GR&R) has been conducted as the Drive Rod to Diaphragm pull-out testing is destructive in nature. In lieu of actual drive rod to diaphragm assemblies, permanent molybdenum magnets with three different magnetic strengths were used as samples. Three different inspectors were trained as well on conducting the test before they were used as appraisers in the Nested GR&R study.

Results show that the Total GR&R % Study Variance is 6.31%, which is better compared to the industry standard requirement of 10%. The number of Distinct Categories is 22, which is above the acceptable level of 5, which means that the test equipment is sensitive enough to detect variations. Refer to Figure 11 for the summary of the results.



Gage R&R (Nested) for Data(N)

Source	DF	SS	MS	F	P
Inspector	2	2.1528	1.07641	0.435	0.652
Magnet batch (Inspector)	27	66.8714	2.47672	751.093	0.000
Repeatability	60	0.1978	0.00330		
Total	89	69.2221			

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.003297	0.40
Repeatability	0.003297	0.40
Reproducibility	0.000000	0.00
Part-To-Part	0.824474	99.60
Total Variation	0.827772	100.00

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.057424	0.34454	6.31
Repeatability	0.057424	0.34454	6.31
Reproducibility	0.000000	0.00000	0.00
Part-To-Part	0.908006	5.44803	99.80
Total Variation	0.909820	5.45892	100.00

Number of Distinct Categories = 22

Figure 11. Nested Gage R&R results.

4.0 RESULTS AND DISCUSSION

4.1 PDCA – Check phase

To validate the applicability of the proposed destructive test set-up, the following applications were conducted in the study.

4.1.1 Drive Rod Cement Adhesive Pull-out Data Baselining

With the test method and equipment qualified, the next course of action that was done was getting the baseline pull-out test data on the current drive rod cement adhesive used. An n=30 pcs set of samples were tested and Figure 12 shows the results. The P-value is > 0.05, indicating the data is normally distributed and Force to break is at 0.221N mean, with a standard deviation of 0.132N.

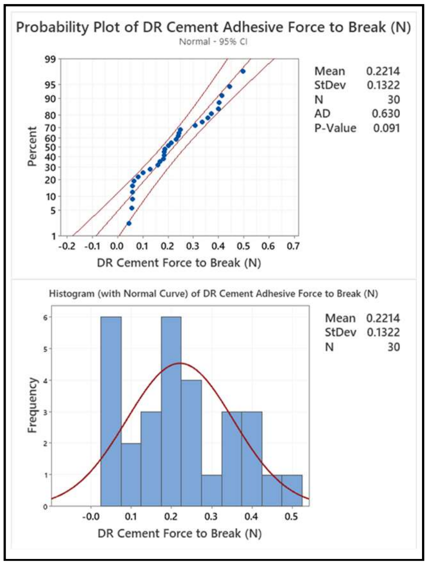


Figure 12. Drive Rod Cement Adhesive Pull-out Data – F, Force to Break in Newtons.

4.1.2 Alternative Drive Rod to Diaphragm Cement Adhesive Testing and Qualification (Practical Application)

An alternative cement adhesive was made available at the time of this project for the purpose of evaluating whether this can eventually replace the current cement adhesive being used. The next step after evaluation of the cement adhesive technical data sheet and cured properties was to put it under the established Drive rod to Diaphragm Pull-out test and compare the results of the alternative cement adhesive with the current cement adhesive.

Figure 13 is an illustration of the results of the Two-Sample T-test conducted between the current cement adhesive and the alternative cement adhesive being evaluated.

The probability plot determines that both sets of data follow a normal curve, with both the P-values > 0.05. The Test of Two Variances returns a P-value of 0.58, which is > 0.05, accepting the null hypothesis (H_0: Both sets of data have similar levels of variation). Lastly, the Two-Sample T-test returns a P-value of 0 which is < 0.05, rejecting the null hypothesis (H_0: Both sets of data have similar means) and accepting the alternative hypothesis (H_a: Both sets of data have dissimilar means). Boxplot data also shows that the alternative cement adhesive Force to break is larger at 0.701N compared to that of the current cement adhesive's 0.221N. It is concluded that from a Pull-out test perspective that the alternative cement adhesive is better compared to the current cement adhesive.

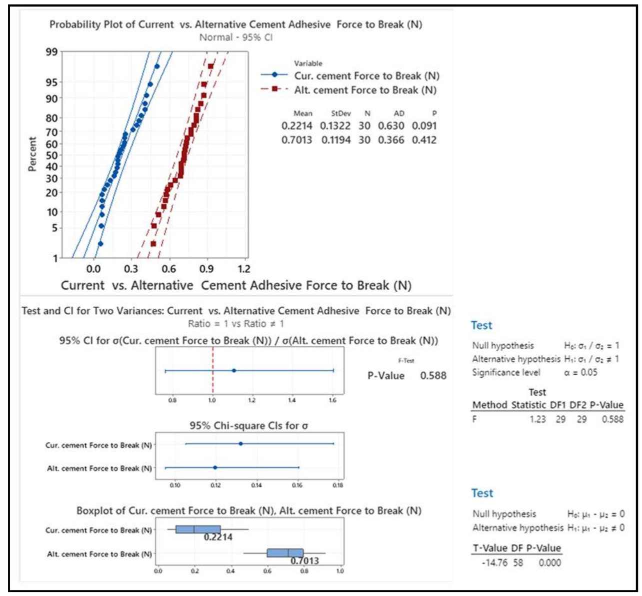


Figure 13. Current Cement Adhesive vs. Alternative Cement Adhesive Force to Break (N) comparison.

The alternative cement adhesive got approval to proceed to the next steps of Qualification which are the sample build and Reliability tests. Figure 14 shows that the alternative cement adhesive passed all reliability tests required for implementation.

Based on the overall results of the Qualification, the current cement adhesive was replaced by the alternative cement adhesive.

Item	Test	Condition	Results
1	HALT	BA is continuously driven at voltages higher than the nominal voltage drive level, while being exposed to elevated levels of temperature and % relative humidity for 6weeks	PASS
2	mV level Stress Test	BA is continuously driven at elevated voltages (twice the voltage setting of HALT in terms of dB) for 1Hour	PASS
3	Temperature Humidity Cyclic Tests	BA is exposed at 10 cycles of 24hrs each at elevated temperatures, %Relative Humidity and reduced temperatures, % Relative Humidity	PASS

Figure 14. Alternative Cement Adhesive Reliability Test results.

4.1.3 Statistical Process Control Set-up and Implementation

From the start of the project, the main objective was to implement assembly-level testing to detect probable reliability failures of the drive rod to diaphragm connection. With this objective in mind, it is necessary to have the drive rod to diaphragm pull-out test as a statistical process control test.

The frequency of testing was set at 10 pcs before the start of the shift. A lower control limit is being set to monitor out-of-control conditions. Please see Figure 15 for the Xbar-S Chart data.

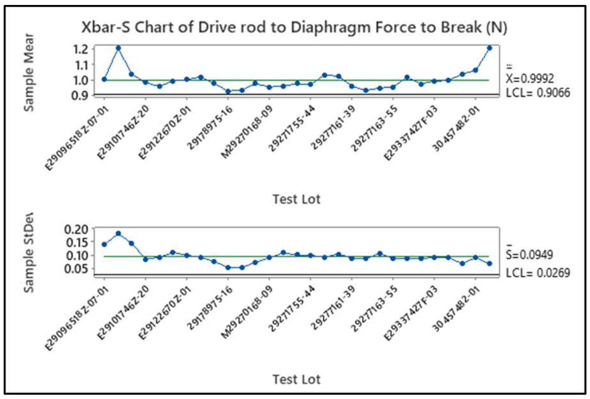


Figure 15. Xbar-S Chart of the drive rod to diaphragm pull-out test data

4.2 PDCA – Act Phase

With the results and success of the project being demonstrated after its implementation on Model "X", the team is now positioned to leverage this test methodology as a foundation for improving other models in the Knowles portfolio of Balanced Armature (BA) Drivers. Several projects have been initiated to achieve this objective. Work Instructions and Control Plans have been revised as part of the documentation process. This project acquired a total of 1.13k USD in savings and would have an opportunity for additional 23.4k USD in savings after the leveraging activities to other lines and models have been completed.

5.0 CONCLUSION

The drive rod to diaphragm Pull-out testing is critical to process control and ensures rapid response to assembly-level reliability failures. This testing is also applicable to be used in characterization, optimization, and design for Quality as the team has demonstrated in the course of the project.

6.0 RECOMMENDATIONS

The drive rod to diaphragm Pull-out testing is recommended by the team to be implemented across all Knowles BA Driver assembly processes – from the established lines up to the new product introduction as part of the design for quality initiative and lessons learned documentation.

7.0 ACKNOWLEDGMENT

The team would like to thank the Operators, Inspectors, Technicians, Trainers, and Engineers for all the efforts in establishing the drive rod to diaphragm pull-out testing and would acknowledge as well the support of the Management Team of Knowles Electronics Philippines in making the project a success.

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9.0 ABOUT THE AUTHORS

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10.0 APPENDIX

Not Applicable