A MEANS OF STATISTICAL PROCESS CONTROL FOR A LOW-VOLUME, HAND ASSEMBLY PRODUCTION LINE

by

Andrew Heitner

S.B. Mechanical Engineering, Massachusetts Institute of Technology (1992)

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

at the

Massachusetts Institute of Technology

May 1994

©1994 Massachusetts Institute of Technology
All rights reserved

Signature of Author____________________
Department of Mechanical Engineering
May 1994

Certified by____________________
Roy Welsch
Professor of Statistics and Management Science
Thesis Supervisor

Certified by____________________
George Chryssolouris
Lecturer, Department of Mechanical Engineering
Thesis Supervisor

Accepted by____________________
Ain A. Sonin
Chairman, Department Graduate Committee

Eng.
MASSACHUSETTS INSTITUTE
AUG 01 1994

A MEANS OF STATISTICAL PROCESS CONTROL FOR A LOW-VOLUME, HAND ASSEMBLY PRODUCTION LINE

by

Andrew Heitner

Submitted to the Department of Mechanical Engineering May 1994
in partial fulfillment of the requirements for the degree of Master of Science.

Abstract

This thesis represents work done towards implementing a means of data-driven process control on a production line which produces medical ultrasound imaging equipment. Because the line is a hand assembly operation and because the line produces extremely low volumes of product, methods other than traditional statistical process control were developed. These methods include specially designed check sheets, moving window Pareto charts, and CUSUM SPC negating outliers wherever possible. Included are examples of how the process baseline was established prior to the implementation of the data collection techniques, through both engineering analysis and the use of Taguchi robustness optimization experiments. Results are presented showing the effectiveness of the scheme, and recommendations are made for further improvements to the line.

Thesis Supervisors: Professor Roy Welsch
Professor of Statistics and Management Science

Professor George Chryssolouris
Lecturer, Department of Mechanical Engineering

Acknowledgements

I take this opportunity to thank all those without whom this thesis and all my work at MIT would not have been possible.

First, thank you Prof. Roy Welsch for giving me the opportunity to work on such an interesting project. I am grateful that you had the confidence in me to allow me the unique experience of working with Company X. Thank you Prof. George Chryssolouris for giving me the opportunity to work with you and for all the assistance you have provided since I've known you.

I thank also Company X for providing the funding for this thesis and for treating me so professionally and so personably. I thoroughly enjoyed my time there. A special acknowledgement is due to my supervisor at Company X, Al Bond, for the countless hours of discussion and advice throughout this project. Thank you also to my manager at Company X, Ashok Tewari, for giving me the opportunity to work in the mechanical transducer group and for providing me with all the necessary support; to Kash Nama, Dan Feng, and the rest of the engineers in the transducer manufacturing group; and to the transducer assembly line workers: Angela Desousa, Lois Parker, Marie Claude, Francisco Espinola, Elaine Brito, Susan Maxwell, Maria Guerrero, Shelly Constaneau, Tom Carter, Yong-Phil Lee, Don Bartlett, and Rosa Gomez for treating me so well and for making work fun.

Thank you to the buddies who held down the fort back in the Lab: Hui Nam, Alvin Ramsey, Velusamy Subramaniam, and Andrew Yablon. You guys have been a pleasure to know and to work with.

I must give a special thanks to the people who really made grad school a fun and memorable experience. The chicos: Todd Simson, Alex Medina, Sir Vic Antaramian, and fellow scribe Mike Duffy. The chicas: Debbie Wallis, Marivioli De La Rosa, and Josette Fullana.

Finally, my most sincere appreciation to my family, my parents Herb and Joyce, my brother Eric, my sister Sharon, and my grandmother Edith Heumann. I am grateful for everything.

Table of Contents

I. Introduction

Company X [the name of the company and its products have been changed throughout this thesis to maintain confidentiality] produces medical equipment which allows doctors to view the internal organs of a patient's body. These devices use ultrasound imaging technology to create a real-time image of the internal organ as it is working inside the body, without the need for surgery and, in most cases, the procedure is non-invasive.

The production line on which this research took place produces two models of cardiac ultrasound imaging transducers. For both models of mechanically-driven transducers, cycle times have been high and yield rates, measured at final assembly, have been moderate. There was also little means for determining where in the sub-assembly processes the problems that contribute to high cycle times and moderate yields were occurring.

The broad objective of the project, then, was to implement a more effective means of process monitoring and process control through relevant data collection and application of statistical techniques to this data. Because the line is operated at extremely low volumes and because production is achieved by hand assembly, not mechanization, traditional statistical process control techniques were not always suitable for use.

Completion of this objective was expected to, and has, aided production engineers in rapidly identifying troublesome areas of production and increasing the efficiency of production. This objective is also in accordance with ISO 9001 manufacturing certification, which Company X has received.

The objective was met in a two-stage process. First, steps were taken to establish the process baseline identifying troublesome areas, finding the root cause of the problem, and solving the problem. Next, a means of data collection was applied to the process. Ultimately, the two stages were reversed, where now data collection helps locate the troublesome areas and identify root causes.

Two forms of data collection have been implemented. Wherever possible, traditional statistical process control (SPC) was used, primarily through the use of cumulative sum (CUSUM) charts. Where no effective metric could be found, *ad hoc* data collection schemes by the operators were used.

Results of these efforts in terms of improving yield and reducing cycle times have, to this point, been encouraging, but not outstanding. The results provided within show the effectiveness of the two-stage process. Cycle times and yields are expected to improve as the changes to the process, also described within, take hold. Moreover, the results point out places in the process where future changes should be made to increase the efficiency even further. Recommendations for these future changes are also presented.

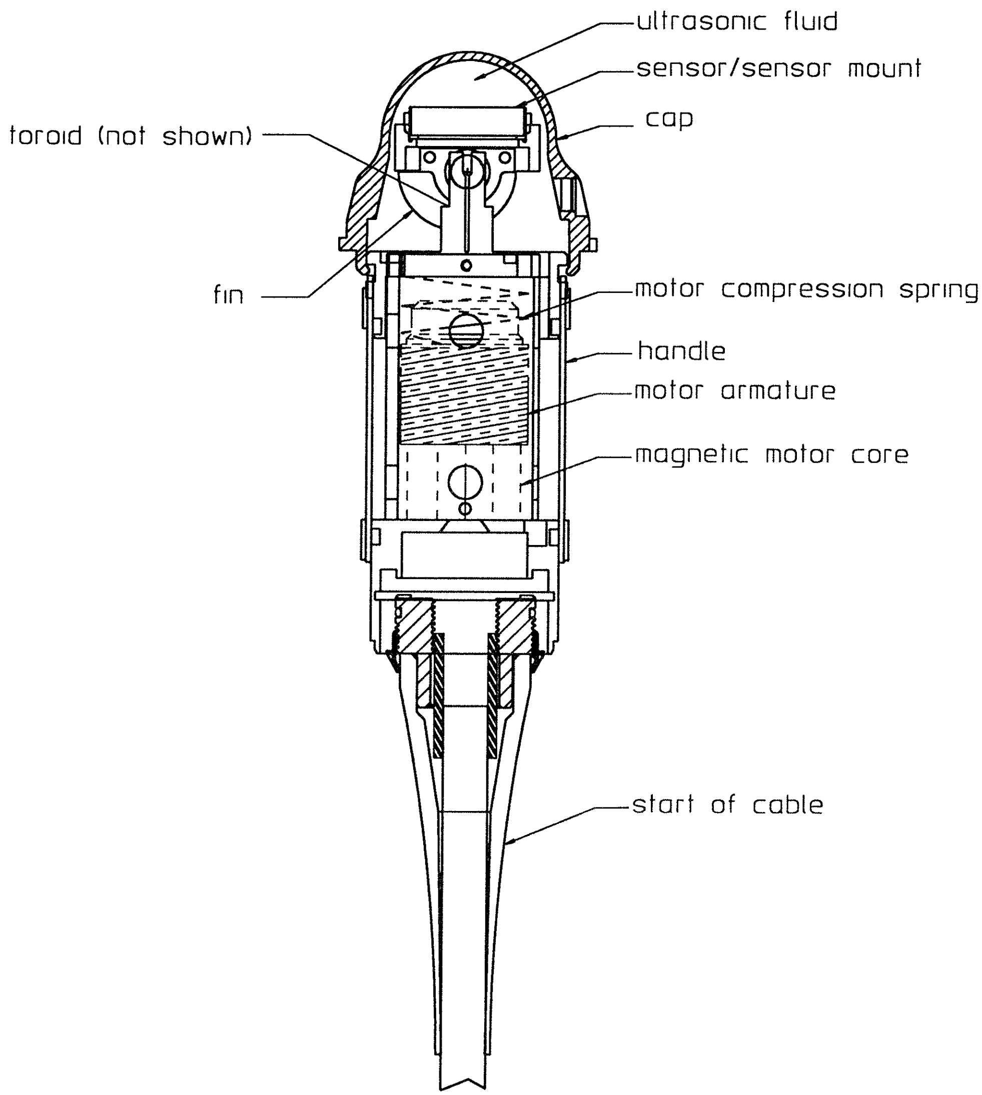


Fig. 1.1 Schematic diagram of the internal parts of the Model A transducer

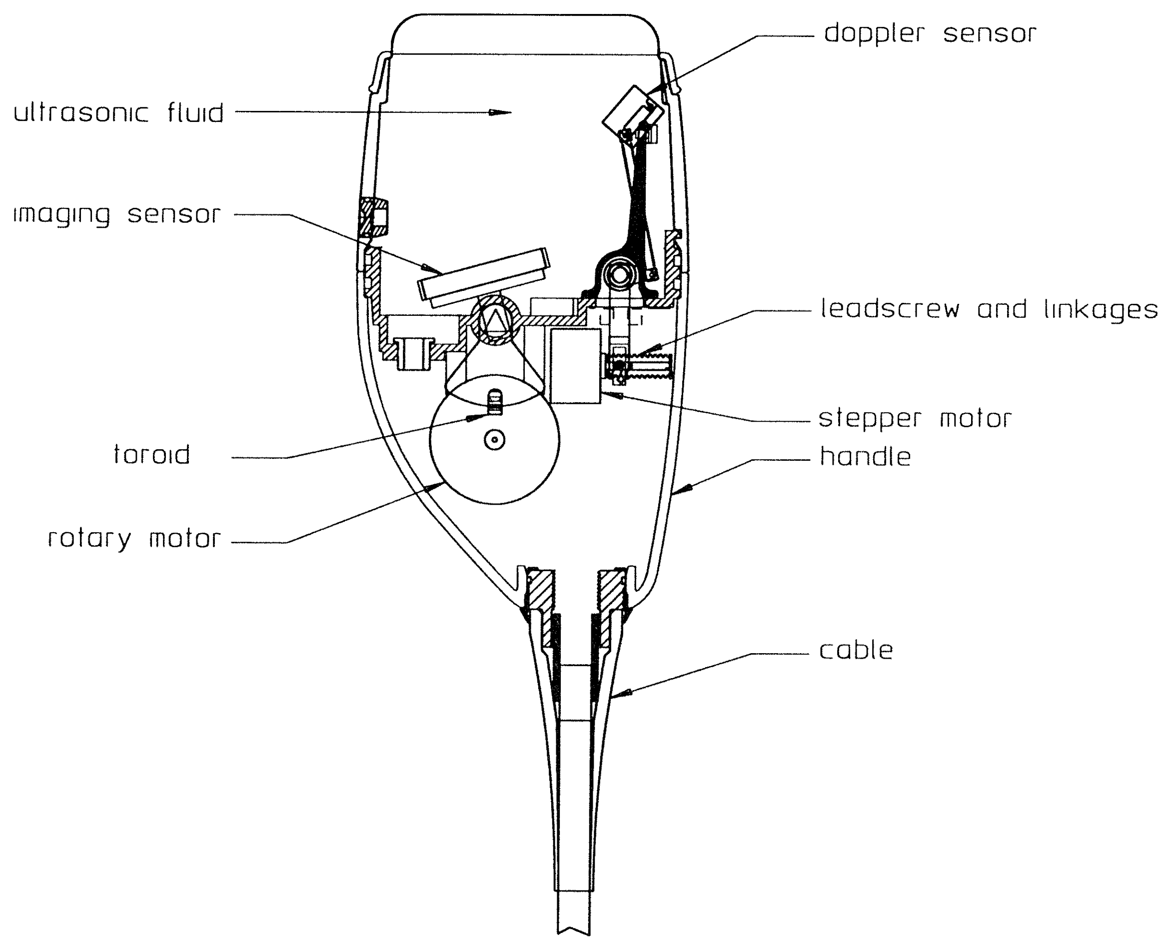


Fig 12 Schematic diagram of the internal parts of the Model B transducer.

1.1 Description of the Product

The production line on which this research took place produces mechanically driven cardiac ultrasound imaging transducers. These devices, when operated in conjunction with the System E electronics, software, and cathode ray tube system, produce a non-invasive real-time image of the heart beating inside the chest cavity. This permits doctors to examine and diagnose heart conditions to greater accuracy than afforded by stethoscope, yet without having to resort to surgery.

There are two types of transducers produced on this production line: the Model A and the Model B transducers (see Fig. 1.1 and 1.2). The Model A transducers can produce only an image, while the Model B transducers have a second sensor which provides information on the flow of blood through the heart. The shape of the Model A transducer approximates a cylinder 5" in length by 2" in diameter. The shape of the Model B transducer approximates a box 5" in length by 3" wide by 1" thick.

Because significantly more Model A transducers are produced than Model B, the focus of the majority of this paper will be the Model A transducer.

A brief description of the technical aspects of the product—how it works, what the component parts are, etc.—is necessary to understand how the product is built and what are the manufacturing challenges associated with producing it.

A schematic diagram of the internal parts of the Model A ultrasound cardiac imaging transducer is shown in Fig. 1.1. The motor consists of a wire-wound armature set around a magnetic core. By sending a varying electric current through the armature, the motor is propelled linearly back and forth. A tow rope (not shown) is attached at one end to the linear motor and at the other end to the transducer's sensor. The sensor is mounted on a pivot, so that as the motor pulls back and forth, the sensor is swept through an arc of approximately 100 degrees.

A compression spring attached to the bottom of the motor armature and a torsional spring attached to the sensor are utilized to allow the motor to both "push" and "pull" the sensor through its full arc. The tension in the torsional spring is adjusted on the line to exactly balance out the tension in the compression spring.

The position of the sensor at any time is known via measurements taken from the fin/toroid system. A metal fin is attached to the sensor mount. As the sensor sweeps out an arc, the fin passes through a toroid that is mounted to the transducer base. The shape of the fin is such that the inductance through the toroid changes as the fin passes through it. By measuring the inductance across the toroid, the position of the sensor is known to high accuracy.

Knowledge of the exact position of the sensor is critical to the reproduction of an image. The sensor is a piezoelectric material that produces pressure waves in the ultrasonic frequency. This ultrasonic pressure wave is able to permeate the soft tissue of the human body (to a certain depth) until the wave encounters a structure, such as the heart. When the wave hits the structure, it is reflected back towards the sensor. By measuring the time for the wave to complete the

round trip from sensor to the heart and back to the sensor and knowing the speed of sound through the body, it is possible to calculate the depth that the wave penetrated before encountering the heart. By repeating this procedure continuously over the entire arc that the sensor sweeps, a composite image is created.

The sensor, fin/toroid system, and the motor are all set in a bath of ultrasonic fluid. A clear plastic cap sits atop the top-end (sensor and fin/toroid system), permitting the ultrasonic waves to pass through but retaining the oil. The entire assembly sits in a plastic handle.

A cable is attached to the bottom of the transducer. The cable carries the motor drive signal, sensor position signal, and imaging signal between the transducer and the System E system.

The Model B transducer (Fig. 1.2) works similarly. In this case, however, there is both an imaging sensor and a Doppler sensor for measuring blood flow. The imaging sensor is now driven by a rotary motor, rather than a linear motor with a spring, and the fin/toroid system for measuring position is retained. The Doppler sensor is driven by a stepper motor turning a leadscrew attached to the sensor through a series of mechanical linkages. Again, the sensors are immersed in an ultrasonic fluid, and a cable carries signals between the transducer and the System E system.

1.2 Description of the Production Line

The mechanical transducer production line consists of 13-16 employees (depending on production requirements), with 7 full-time workers employed by Company X and the remainder temporary employees paid through an outside employment service. Two or three assemblers are usually assigned to Model B production, with the remainder assigned to Model A production.

Production of Model A transducers can be broken down into three primary functions: sub-assembly production, assembly, and testing.

Sub-assembly production consists of taking raw materials, such as wire, electronic components, or specially-designed piece-parts, and gluing, winding, or soldering them together to create the major parts which comprise the transducer. Examples of sub-assembly production include the motor, cable, sensor mount, and toroid sub-assemblies. Sub-assembly production is generally done by several workers working in parallel.

The assembly stage can be broken into three sequential events: main assembly, fill, and cable attach. In main assembly, all the sub-assemblies (except the cable) are put together into a single working entity. The transducer is then filled with ultrasonic fluid and air bubbles, which may distort the image, are removed from the fluid. In the final assembly stage, the cable and plastic handle are attached to the transducer.

Finally, in the testing stage, the transducer undergoes a battery of tests to ensure both that the image quality is acceptable and that the transducer performs to FDA safety standards. One example of a test at this stage is the tank test, which measures the electrical properties of the piezoelectric sensor within the transducer. As described below, a form of SPC has been implemented on the tank test.

1.3 Project Objective

The stated primary goal of this project was to implement a more effective means of process monitoring and process control to the mechanical transducer production line. There were several reasons that this objective was requested by the engineers at Company X.

1) Limited engineering resources have been allocated to supporting this production line. This puts a premium on the time that an engineer can devote to the mechanical transducer line, and the engineer, therefore, requires a method which will quickly locate problems and aid him in identifying the root cause of these problems.

2) Problems that surface tend to get addressed by the assemblers on the line. These problems at times do not get reported to the engineers, and the root cause is sometimes not found and fixed. The problem may go away temporarily, but may often return. Engineers have found it difficult to gage the efficiency of the line without asking each assembler, "How's it going?".

3) Quality of production has been judged by the sometime misleading metric of first-pass yield. Although this figure is important, it does not accurately account for transducers which fail repeatedly. Moreover, it does not identify the area of production or particular sub-assembly process which is having problems. Also, if these problems do not directly contribute to a failure at final test (i.e. they get reworked before being passed on to final test), the problems may not show up.

There were several factors that presented considerable challenges to the successful completion of this project.

1) The primary obstacle was a lack of effective metrics for measurement. Most orthodox means of process diagnostics and control require continuous variable measurement (for instance, a dimension of a machined part or the cross-over frequency of an acoustic device) upon which to base decisions. The nature of hand assembly, however, does not lend itself to such metrics. How can one quantify how well or how easily several sub-assemblies have been assembled?

In the absence of continuous variables, attribute variables (for instance, fraction non-conforming) can sometimes be substituted. However, the lack of conformance/non-conformance tests at some stages of production and the low production volume prevented the strict use of attribute variables.

2) The line assemblers were not receptive to additional paperwork. The assemblers already felt burdened by the amount of paperwork already required of them. Furthermore, there was the stigma among the operators about any interference that required they do additional paperwork. Some attempts at data collection have been made in the past, but often the assemblers did not understand the need for them.

1.4 Roadmap for the Rest of this Paper

This introduction has given the reader an overview of the manufacturing line which was the focus of this project. A brief description of the product being built, its component parts, and its method of operation was presented to familiarize the reader with the specific items to be discussed. A brief description of the flow of the production line was also presented for this reason. Finally, the objective of the project has been stated, and the motivation for the research have been discussed.

Chapter Two presents a survey of the literature relevant to this thesis. Included are references to works on SPC, SPC for low-volume manufacturing, alternative data-driven process control methods, CUSUM charts, robust SPC techniques, and design of experiments.

Chapters Three, Four, and Five explain the bulk of the work done towards the stated goal. Chapter Three describes some of the measures taken to "fight the fires" and establish the process baseline. Included is a designed parametric experiment for increasing the robustness of a piece of production equipment. Chapter Four presents the different means of data collection that have been developed and implemented on the line. Chapter Five presents some results obtained by the data collection scheme. Also presented is a specific example of how the data collection scheme was used to identify, analyze, and rectify a problem on the line.

Chapter Six lists the author's opinions about the overall success of the project, including a critique of the good and bad points of the data collection scheme. Recommendations for future work which will help the process are also presented.

II. Literature Survey

The pioneering and seminal work which proposes the use of statistics based control charts to understand and reduce the variability of a manufacturing process was done by Shewhart [41] in 1931. His work developed the X-bar (Shewhart) and R (range) charts, primarily for use on high-volume manufacturing processes. The novel idea of the time was to take measurements of the quality of the manufactured product at regular intervals. These measurements then represented a statistical sampling of the overall quality of the output of the process.

By plotting these measurements on a chart versus time, a graphical representation of the performance of the process is obtained. To aid in the interpretation of the charts, statistical control limits were developed to inform the operator or engineer (within a certain confidence) when the process was drifting from its established baseline capabilities. This work also assumed that metrics describing the quality of the manufactured product were easily obtained.

Unfortunately, the bulk of Shewhart's work, both in terms of the academic advancement and in terms of the paradigm shift in manufacturing away from piece part go-no go gage testing and towards statistical process control went largely ignored within industry for decades. Based on the literature available on SPC, it is safe to say that SPC techniques were used on only the smallest of scales until the 1960's, started to take hold during the 1970's, and gained wide-scale interest and adaptation in American industry in the 1980's.

The work of Shewhart and Demming, specifically X-bar and R charts, are sufficient for the high-volume, continuous flow manufacturing that they set out to aid. Once the need for SPC was accepted and adapted by American manufacturing, the demand grew for the further advancement of statistical techniques. As inefficiencies with Shewhart charts arose in particular situations, the literature reflects attempts to find appropriate statistical process control techniques to circumvent these inefficiencies.

The literature, then, contains much work developed as *ad hoc* situations in manufacturing arose. For instance, techniques were developed for low-volume processes [26, 12], for mating SPC with automatic feedback control [6, 39, 40, 19], for batch processes [22], or for processes in particular industries [1, 2, 3]. In addition, there has been some work in developing alternative techniques to SPC, such as Pareto and flow charts, as a means of process control [25, 5, 18, 9, 23, 43]. Several of these are described below.

Hahn's 1993 work [19] is the most complete in discussing all of these issues. He presents a discussion on the impact that using SPC can have on a production line, and gives caveats for using the various techniques. He advocates the use of "data driven analytics" for effective process control of manufacturing lines. He predicts and advocates for the future the use of algorithmic statistical process control (ASPC), a marriage of SPC and automatic feedback control.

There is some work specifically targeting low-volume processes, but these are primarily in the form of case studies for a particular process or industry. Koons [26] describes efforts that were taken to bring a type of statistical process control to the McDonnell Aircraft Co, in which "the myriad number of parts, the extremely large number of part characteristics, and the low-volume nature of [McDonnell's] process necessitated a different approach to applying statistical process control techniques." In it, he advocates studying the processes which produced a part, rather than studying the specific dimensions on those parts. Cullen's work [12] also describes bringing SPC to the aircraft industry.

The work of the AFS Green Sand Molding Committee [1, 2, 3] is a summary of SPC and a description of how it can be effectively used for the specific batch processes found in the metal sand casting industry. The authors largely ignore, however, some of the statistical difficulties associated with trying to control batch processing.

The work of Holmes [22] is founded in the metal casting industry, where low-volume batch processes are used, and he presents a novel technique for dealing with data which is low-volume and may not assume a normal distribution. His dynamic histogram technique, it is claimed, is faster to respond to process changes than X-bar charts and is less sensitive than CUSUM charts to data which may conflict with normality assumptions.

Alternative methods to SPC have also been explored in the literature as a means of data-driven process control. Benjamin [5] and Kenett [25] both describe uses of the Pareto chart. Benjamin demonstrates the effectiveness of Pareto charts through several well developed case studies. He advocates the use of an 80/20 line to determine which problems should be addressed by corrective action. The 80/20 line is a line above which 80% of the failures–either in number or in total cost and usually caused by only 20% of the problems–are found.

Kennett, on the other hand, presents a method for comparing a Pareto chart with a similar chart constructed at a different time and determining statistically (with a certain confidence interval) whether the two charts were constructed from the same process. As such, Pareto charts can function very much like control charts with SPC.

White and Shroeder [43] propose a new type of process control chart, called the simultaneous control chart, in which both the process level and variance are controlled in a single chart. It is claimed that this new type of chart is more robust to outliers and easier to read for personnel with a non-statistics background. Iglewicz and Hoaglin [23] advance this principle, advocating the use of boxplots in place of single points on X-bar and R charts.

Within the realm of traditional SPC methods, CUSUM (cumulative sum) charts were developed as an alternative to X-bar charts. CUSUM charts plot the cumulative sum deviation from target of the measured values. If the process is in control and the only variance about the target is due to natural (random) causes, the plot should stay close to the zero line. When the process goes out of control, however, the plot quickly runs far from the zero line. According to Montgomery [31], CUSUM charts are more sensitive to small process shifts than X-bar charts and are better for plotting individuals, rather than rational subgroups.

Lucas is a major proponent of the use of CUSUM charts and has written several papers on various aspects of these charts. Lucas [28] describes the optimal design of a v-mask scheme for use as control limits on a CUSUM chart, and presents an example of its use from the chemical industry. Lucas and Crosier [29] propose the fast initial response (FIR) feature of the CUSUM control chart, which is intended to provide a rapid alarm for an out-of-control state of a process, particularly during start-up of a process or after the CUSUM has been reset following an alarm situation. Gan's paper [16] is an amalgam of the two previous papers; he proposes methods for determining the optimal design parameters of a CUSUM chart, both with and without the FIR feature.

Important also is the notion of robust control charts, control charts which minimize the number of false alarms that occur despite the presence of outliers in the data. Rocke [38] presents a method for measuring the robustness of various control charts. His findings indicate that standard X-bar and R charts are the least robust type of charts, and presents a discussion on the use of robust CUSUM charts.

Hawkins builds on this work by proposing a method of making CUSUM charts robust, called winsorization. This method limits the effect of outliers on the statistics of the CUSUM chart, without affecting the performance of the chart in identifying out-of-control processes. Rocke and Zhou [37] present an EWMA (exponentially weighted moving average) chart which is robust not only to outliers, but also to faulty assumptions of normality in the data.

All of these papers, however assume the presence of a continuous variable metric which is an accurate measure of the quality of the process output. The academic work has focused, then, on developing the tools for manipulating the measurements of these metrics to properly identify an out of control process. One of the major difficulties associated with developing the techniques described in Chapters 4 and 5 for a hand-assembly production line was identifying a quality metric to be used. It is difficult to associate a continuous variable metric to the question, "How well was that unit *assembled*?". This question has not been addressed in the literature. It is likely that it must be addressed on a case-by-case individual basis, but it is the intent of this paper to present the method used for the Company X production line, such that it can be used as a reference point for future work on other lines.

An example of designed parametric experiments used to increase the performance of a sub-assembly process is described within. There exists a large body of literature on the design and use of parametric experiments. The use of designed parametric experiments is a useful technique for improving the output of a process–both changing the level and decreasing the variability. This is often done prior to implementing SPC, such that the baseline against which the process will be measured is at a desirable level.

Taguchi's methods for designed parametric experiments [42] have been employed here. The emphasis of Taguchi's work over traditional experimental design work is on improving not just the level of the output of the process, but rather on improving the robustness of the process. A robust process is one that performs consistently well despite the presence of noise factors that commonly occur in a manufacturing setting.

Phadke [35] and Clausing [10, 11] are among the most vocal supporters of Taguchi's techniques. Their works are excellent references, on both the technical details of running designed parametric experiments and on explaining the logic behind Taguchi's robustness philosophy. Hahn [20] provides a good overview of designed parametric experiments and the effectiveness of using them. He also presents helpful suggestions for the successful use of designed experiments in real-world applications.

III. Establishing the Process Baseline

The necessary precursor to implementing any means of data-driven process control on a production line is to ensure that the process is under control. The nature of passive, data-driven process control is to first establish a baseline that is typical of how the process naturally performs. Then, continuous hypotheses are made against the baseline, testing whether or not the process has significantly deviated from an "in control" state.

This chapter presents three examples of actions that were taken to establish the baseline for the mechanical transducer process. Simultaneously, a means of data-driven process control was being implemented. The first two actions (Sec. 3.1 and 3.2) were taken in response to problems that occurred on the line, threatening production output. The third item is an example of how Taguchi-style designed experiments were used to create a more robust and improved process.

3.1 The Hitting Cap Problem

The Model A probes are tested at the final test station to ensure that the movement of the imaging sensor will not be impeded by the cap if the pliable cap is deflected when pressed up against a patient's body. At one point, a high number of probes failed this test, and a low final yield percentage resulted. An investigation determined that the caps were the root cause of the problem. By working with the supplier of the plastic caps, a long-term solution was implemented, ensuring that the process would be under control in the future.

3.1.1 Description of the Problem

The caps on the Model A probes sit over the top end of the probe (see Fig. 1.1), and are used to provide a barrier between the rapidly moving sensor within the transducer and the patient's skin. The caps are made of a clear plastic.

Because the caps can be deflected slightly when the transducer is pressed against the chest of the patient, there is the possibility that the deflection of the cap will interfere with the movement of the sensor and cause the transducer to cease operating. To ensure that this will not be the case, a test is conducted as part of the final test procedures that each transducer must pass in order to be shipped. For the "hitting cap test," the transducer is held upside-down and pressed against the spring resistance of a graduated force gage. The cap must withstand a specified test load force without interfering with the moving sensor in order to pass. The motor signal of the transducer is monitored on an oscilloscope to detect interference between the sensor and cap.

Over the course of one week, a high number of transducers failed this test, with a large fraction of these failing a second time after being reworked. This unusually high failure rate nearly caused a complete halt in production. An investigation was launched to determine the root

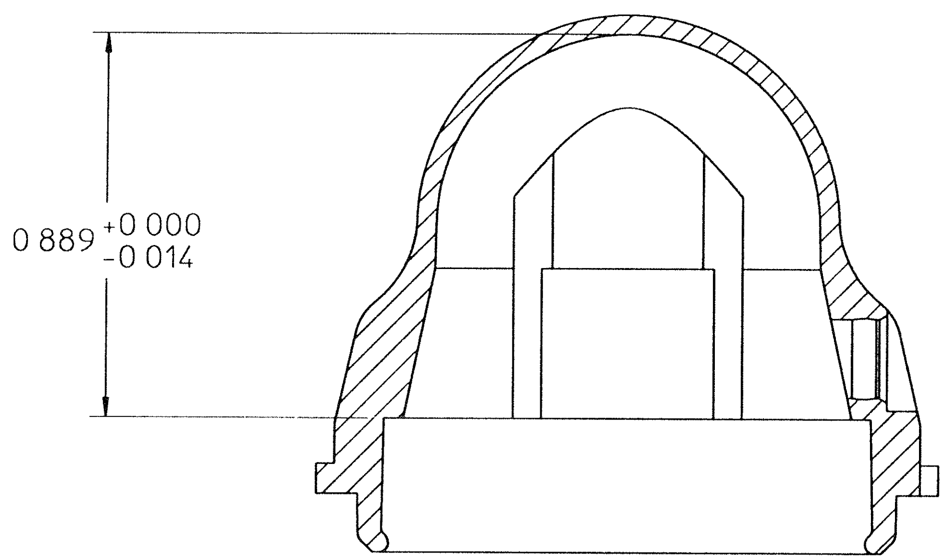


Fig 31 Specification drawing showing inside height dimension for the caps of Model A transducers

cause of the problem, and to then enact a solution which would alleviate the problem and get the process back in control.

3.1.2 Determining the Root Cause of the Problem

The first step in the analysis was to determine which component of the transducer was causing the problem. Possible culprits included: the top end, which could have been machined improperly; the sensor/sensor mount assembly, which could have been glued improperly, such that the sensor was sitting higher in the mount than usual; or the cap, which could have been off in a number of dimensions which would cause the inside top of the cap to be closer to the sensor than intended.

A set of experiments were run by changing components in a series of failed transducers. By deductive reasoning, it was determined from these experiments that the caps were at fault in causing the transducer failures.

The measurements of 50 caps used for transducer production were then checked against the specification drawings for the caps (see Fig 3.1). All of the measurements were within the specification limits set out in the drawings. However, the measurements for the inside height of the caps were all to the less-conservative (smaller clearance between sensor and inside top of the cap) side of the spec. The print dimension for the inside height is listed as .889" with a tolerance of +.000" and -.014".

Seven of the caps used on transducers which had failed the hitting cap test measured from .0095" to .0155" below the nominal value of .889" (inside heights of .8795" to .8735" respectively). 43 caps which were in inventory ready to be used for production transducers measured from .0065" to .009" below nominal, with an average of .008" below nominal.

A sample of 23 caps out of a shipment of 500, which were in stock waiting to be released to the line inventory, were also measured to compare the value of their inside heights to the .889" nominal value listed on the print. These caps measured from .0025" to .009" below nominal, with an average of .007" below nominal.

Finally, as a comparison with the types of caps that had been received in the past, 9 caps were removed from available decommissioned customer exchange transducers. These transducers had been built at least 18 months prior to the occurrence of the hitting cap problem. The inside height of these caps measured from .0036" <u>above</u> nominal to .004" below nominal, with an average of .0006" below nominal.

It was clear that the process used to manufacture the caps (done by an outside vendor) had drifted over time. Whereas the inside height of the caps had once been very close to the nominal value of .889", the previous two shipments had yielded caps which had inside heights much smaller than the nominal, even though the measurement was still within the specification.

A investigation was then launched to determine whether the wide specification limits (+.000" to -.014") were actually valid. This investigation examined all the factors that could affect the clearance between the sensor and the inside top of the cap to see how robust the specification limit was. Aside from the deviation from nominal of the inside height of the cap, the two factors that were investigated were: the deflection of the cap under the specified test load, and the deflection of the cap due to stresses caused by tightening the locking ring to hold down the cap.

Compression Deflection Test

Two caps from among the 50 in the production queue were compressed on an electronic tensile tester. Two caps from among the 9 decommissioned customer exchange transducers were also tested. All 4 caps behaved similarly, indicating that there was no difference in the elastic properties of the caps from different shipments. The results were as follows:

- test load force produced .010" of deflection
- doubling the test load force produced .020" of deflection

- a cap spring constant of .010"/test load, linear over the operating range of the transducer

Locking Ring Torque Deformation Test

A probe was assembled with one cap from among the 50 in the production queue. At first, the locking ring was tightened by hand, and the force required to cause the sensor to hit the inside top of the cap was measured. Then, the locking ring was torqued to its full process spec, and the hitting cap force was measured again. This test was performed twice, and was done to see if fully tightening the locking ring causes the dimensions of the cap to change, as compared with the relaxed condition. The results were as follows:

- the force at which the sensor hits the cap is degraded by ½ test load when the locking ring is fully torqued, as compared to hand tightened

- using the identified spring constant of .010"/test load, the ½ test load degradation indicates that the inside height of the cap is lowered by .005" due to the torquing of the locking ring

Tolerance Stackup

A layout of the Model A assembly shows a nominal clearance of .029" between the sensor and the inside top of the cap. From the series of experiments performed, the following shows how much this clearance is reduced by major effects.

1. Using a cap of .010" below nominal: .010"
2. Hitting cap test load specification: .010"

3. Locking ring deformation: .005"

Total: .025"

The sum of these major effects leaves a clearance of only .004" (.029" - .025"). This is a very small amount, and can be negated by the tolerance stackup or variance in production of any of the following factors: sensor thickness, sensor mount geometry, amount of glue on the senor mount, tolerances in top-end machining, and variation in internal shape of the cap.

Thus, it became evident that the root cause of the hitting cap problem was the inside height of the caps. A drift in the process by the outside manufacturer, although still within the agreed-upon specifications, was at fault for causing the shallow inside height of the caps.

3.1.3 Actions Taken

Because the root cause of the problem within the transducer assembly process was an out-of-control cap molding process at the factory of an outside vendor, getting the transducer process back in control required getting the molding process back in control.

The vendor was contacted, and through a series of parametric experiments identified the factors which influenced the inside height of the caps, and determined how to reduce the variability of cap production.

With the above analysis performed, new specification limits for the inside height of the cap were set. On the low side, the limit was set at -.005" (.005" below the nominal value of .889"). This was selected to ensure a sufficient amount of clearance between the sensor and inside top of the cap, even after accounting for the deflection due to test force loading, torquing of the locking ring, and tolerance stack-up of the other top end components.

On the high end, the limit was set at +.002" (.002" above the nominal value). Because this value was outside the original spec limits, approval from R&D had to be obtained. This value was selected in order to give the cap manufacturer a window of .007" in which he could deliver acceptable parts, the natural variation of the cap manufacturing process.

3.1.4 Results

The analysis described above and the actions taken have been very effective in eliminating the hitting cap problem, and getting the transducer manufacturing process in control. There have been no reported transducer failures due to hitting cap since the manufacturer shipped the first batch of caps under the new specification limits. Furthermore, the manufacturer has not reported any problems meeting the tighter specs.

3.2 Audible Noise Problem

The Model A probes are tested at the final test station for noise audible to the human ear during operation. A rash of failures of this test created a problem situation for the mechanical transducer production line, causing low production yields. An investigation determined that the noise came from the shaft/spring sub-assembly, and that the root cause was both the gluing and the brazing of the shaft/spring sub-assembly. Several short term solutions were implemented. Several long-term options were also examined, but the most cost effective solution was to maintain the standard method of production, but increasing operator training.

3.2.1 Description of the Problem

The presence of audible noise during the operation of the transducer is both an annoyance the sonographer and the patient and an indication that some of the moving parts within the transducer are faulty. It is for this reason that the probe is run and examined to be sure it is free of noise and vibration during final testing. Part of the test consists of checking the probe with an accelerometer and examining the amplitude of the vibrations within the audible spectrum. The amplitude of such vibrations must be less than a specified dB for each 10 Hz frequency component. The second part of the test consists of listening with the unaided ear while the probe is running. If there is any unusual noise, the test is failed and the probe must be reworked.

A tinny, scraping sound was heard on several Model A probes, even though the decibel level from the vibration meter was within spec. Over the course of 3 weeks, a high number ofsuch failures occurred, with a large fraction of these failures occurring a second time on probes that had failed once and then been reworked. An investigation was launched to determine the root cause of the problem, and to then enact a solution which would alleviate the problem and get the process back in control.

3.2.2 Determining the Root Cause of the Problem

By changing out different elements on the noisy probes one at a time, it was determined that the shaft/spring sub-assemblies (see Fig. 3.2) were causing the noise. The mechanism by which the shaft/springs were creating the noise, however, still needed to be determined if a long-term solution were to be implemented.

Three of the probes that had failed were disassembled, with the top end left intact for examination. Analysis showed that the noise occurred on that portion of the sweep in which the motor is traveling upwards, such that the drum and bearings in the shaft/spring sub-assembly (see Fig. 3.2) are pushed up towards the top end post on the fin side.

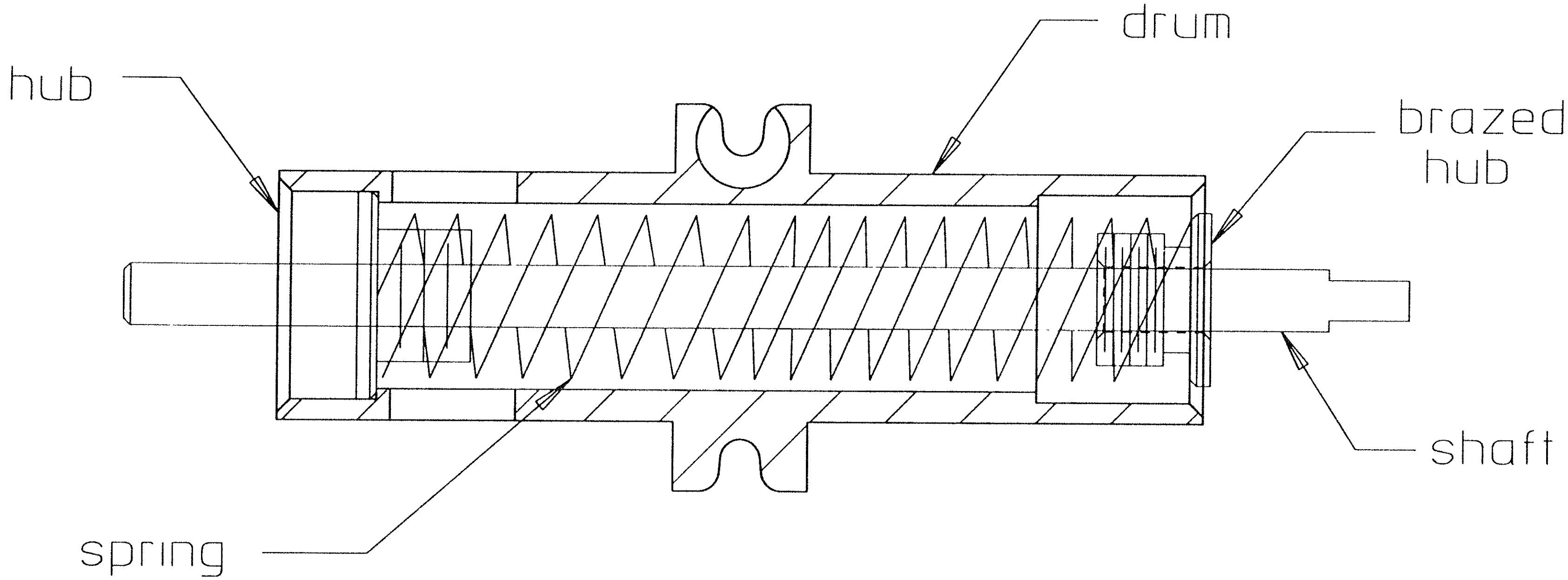


Fig. 3.2 Shaft/spring sub-assembly for the Model A transducer.

Moving the sensor by hand showed that the noise phenomenon is inertia related. When the sensor is moved slowly, no noise is heard; however, if the sensor is accelerated or decelerated rapidly, the scraping becomes obvious. With the transducer plugged in and running, the noise could be quieted if the entire drum assembly was carefully pushed away from the top end post on the fin side.

The tinny scraping sound, the fact that the noise occurred when the drum and bearings are pushed to one side, and the fact that the phenomenon is inertia related indicated that the root cause of the problem likely stemmed from parts intended to be stationary moving with respect to one another. Some differences in the batch of shaft/springs used in the noisy probes were noted as compared to previous batches of shaft/springs:

1. The springs were not fully wound down onto the brazed hub, and improper amounts of glue were used. The springs are supposed to be wound such that the last coil just kisses up against the hub flange. That coil is supposed to have glue only under its tip and along the side up to where it stops kissing the hub.

2. There was excessive solder on the bottom of the brazed hub. This often led to the hub being cocked with respect to the shaft, and the spring crooked with respect to the shaft.

The first finding demonstrated that the noise was likely caused by the coil of the spring coming dislodged and whipping around the hub when there was sufficient acceleration applied to the sensor. The spring scraping against the hub was likely the cause of the tinny scraping noise.

The second finding demonstrated that the noise could have also been caused by the scraping of the spring coil windings against the inside of the drum. Because the springs were not concentric with the axis of the shaft, when the shaft/spring sub-assembly rotated so as to compress the spring coils together, the coils could have ridden up over one another and made contact with the inside of the drum.

Both findings were addressed in the corrective actions taken to try to fix the audible noise problem and get the transducer production process under control.

3.2.3 Actions Taken

In the short term, three actions were taken. First, an experienced assembler screwed the springs down further against the brazed hubs and reglued them. It was noted that most of the audible noise problems occurred after the assemblers rotated assignments. This meant that the shaft/spring sub-assemblies had been produced by an assembler new to the assignment. Thus, the second action taken in the short term was to assign a different assembler to produce shaft/spring sub-assemblies. This seemed to have the greatest impact on solving the audible noise problem in the short term.

Third, the brazing machine which is used to join the hub to the shaft has settings for temperature and dwell time. By adjusting these parameters, the quality of the braze and the skewness of the hub with respect to the axis of the shaft was improved. However, this improvement was only slight. It was then noted that the solder paste mix that the inexperienced operator had been using contained too little water as compared with what had been used in the past. So, in addition, the composition of the solder paste was returned to its original recipe.

In the long term, other methods of manufacturing the shaft/spring sub-assembly were investigated. The two methods examined were: laser welding the hub onto the shaft, or machining the hub and shaft assemblies out of a single piece of metal. The intent here was to remove the inaccuracies associated with brazing, and cut down on the scrap produced by this process, thereby also cutting the production cost.

After careful analysis, however, it was determined that both of these methods were not cost effective to implement, particularly in light of the low production volumes. Therefore a long-term solution using the existing manufacturing technique was desired.

Because the problems with the shaft/spring sub-assemblies had been identified by experienced operators, it was determined that the best long-term solution to the audible noise problem was to ensure a better transfer of knowledge between assemblers when assignments were switched. This has been particularly emphasized in the production of shaft/spring sub-assemblies, and it seems to have worked. Further recommendations for improved transfer of knowledge are discussed in Chapter 6.

3.2.4 Results

Both the short- and long-term solutions have been effective in solving the audible noise problem and getting the process in control. In eight months since the solutions have gone into effect, there has been only 2 reported audible noise problems. These were isolated occurrences, however, and no further corrective action was taken.

3.3 Toroid Winder Machine Robustness Optimization Experiments

The toroid sub-assemblies are parts critical to the operation of both the Model A and Model B probes. In each transducer, the position of the sensor is determined by measuring the inductance across the toroid as a metal fin fixed to the sensor is passed through a slot in the toroid. Proper calibration of these toroids is essential.

The toroids are produced using the following process: In the mechanical transducer production area, thin gage wire is wound around a ferro-magnetic core by an assembler operating a toroid winding machine. The assembler then glues the wound toroid to a plastic base, and sends the mounted toroids to a separate department, where a cut is made in the core, creating the slot for the fin to pass through. Back in the mechanical transducer production area, the windings on the toroids are adjusted (pushed closer or further apart) until the inductance through the toroid is within specification. The windings are then glued in place, and the toroid sub-assembly is complete.

Putting the windings on the magnetic core via the toroid winding machine is the most critical, and least reliable, part of this process. The toroid winding machine is operated as follows: Wire is taken from a master spool and a fixed number of revolutions are loaded onto a shuttle. As this is occurring, the operator guides the wire into correct position on the shuttle with his finger.

A magnetic core is loaded onto the machine and held in place under pressure from three guide rollers. As the core rotates, the shuttle passes through the center of the toroid, leaving the desired number of winds on the toroid. The spacing and the tightness of these winds about the magnetic cores directly affects the inductance through the toroids.

3.3.1 Motivation for Taguchi Method Designed Parametric Experiments

Producing quality toroids—toroids which could easily and quickly be calibrated to within the inductance spec—had long been considered something of a "black art" within the mechanical transducer area. The winding machine was temperamental and unpredictable. Especially after undergoing processing in another department, the quality of the toroids varied dramatically both within a batch and from batch to batch. It took an operator several batches to become proficient at producing toroids which could then be used in production transducers. Even an experienced operator would expect that 25-30% of the toroids wound and cut could not be calibrated and had to be scrapped, only a 70-75% yield.

The fact that the toroid winder machine was considered a "black box"—no known or mathematical relationship between all controllable setting and quality of output exists—indicated that improvements to the toroid winding process had to be done experimentally. Parametric designed experiments using orthogonal array was the best way to sample all settings of factors simultaneously while keeping # experiments low. The large variation in quality of toroid production indicated that a robustness optimization would most dramatically increase the quality of the process. Taguchi's methods, emphasizing the quality loss function and signal-to-noise ratios, were desirable due to the emphasis on making the process robust to noises and decreasing the variability of product output.

The overall goal of the designed experiments, therefore, was to ultimately enable the assemblers to consistently produce toroids which are both able to be tuned to within specifications, and which are as consistently close to the target value initially. This was accomplished by: selecting control factors on the machine which affect in some way the quality of the output; identifying and accounting for any noises that can adversely affect the quality of the output; identifying metrics by which to judge the quality of a produced toroid; and establishing an effective and economical experimental program, that follows an orthogonal array for varying the levels of the control factors.

Section 3.3.2 below describes how the experimental program was designed. Sections 3.3.3 and 3.3.4 then describe the results obtained from two rounds of experiments and present the experimentally determined optimal settings for the control factors. The change to the production process, however, did not occur in time to present data showing the improvements seen by the process following robustness optimization experiments.

3.3.2 Design of the Experimental Program

Identifying the Control Factors

The control factors for a set of designed experiments are those parameters whose levels the experimenter is free to set, during both the running of the experiments and the everyday operation of the equipment. For the toroid winding machine experiments, many sources were consulted in order to determine which controllable parameters on the winding machine could possibly affect the quality of the toroid winding. To achieve the stated goal of the experiments, the optimal settings for these factors which would optimize the robustness of the toroids built would be identified.

Following discussions with the operators, examination of the machine operating manual, and consultation with the manufacturer, the following parameters were identified as control factors:

1) # Load winds—the number of winds loaded onto the shuttle prior to toroid winding

2) Finger position—the position in which the operator is holding the slack wire during the loading of the shuttle

3) Roller pressure—the pressure with which the rollers hold the toroid in place during toroid winding

4) Core speed—the rotation speed of the core as the windings are being applied

5) Wind speed—the speed at which the shuttle turns during core winding

Selecting the Levels for the Control Factors

Because all of the identified control factors could take on many values (as opposed to on-off 2-level factors), it was desirable to establish 3 experimental levels for each of the control factors, so as to be better able to identify maxima and minima in the experimental results. For the first round of experiments, the existing nominal value was taken as the middle level for the factor. Some preliminary runs on the machine indicated approximately how far from nominal the control factors could be set and still wind the toroid properly. The high and low values were then taken as the remaining two settings for the factors.

Using this methodology, the following settings were established for the control factors for the first round of experiments (Table 3.1):

Factor	Lo	Middle	Hi
# Load Winds	10	13	16
Finger Position	none	1 finger	2 fingers
Roller Pressure	-1/8 turn	nominal	+1/8 turn
Core Speed	18	20	22
Wind Speed	30	40	50

Table 3.1: Control factors and their experimental levels for the first round (L_{18}) of toroid winder robustness optimization experiments.

Identifying the Noise Factors

Noise factors are those parameters which tend to cause the variation in the quality of the product, and over which the experimenter has no direct control. Phadke [34] classifies noise factors for the optimization of a product design as: external—the environment in which the product operates or the load to which it is subjected during operation; unit-to-unit variation—the variation inherent in the manufacturing process used to produce the product; and deterioration—the wear seen in the product over time. In the case of optimizing a production process, however, the two types of noise are: external—the environmental conditions of the factory in which the process is operating; and unit-to-unit variation of the raw materials coming into the production process.

When performing a robustness optimization experiment, it is important to identify the noises inherent in the particular product or process in question. The optimization should then be conducted under the most severe noise conditions. In this way, the control factors will be set to the levels which produce a product that is robust to the most severe noises seen in the field or in the factory. Robust products and processes are the goal of the practitioners of Taguchi's philosophy of modern manufacturing techniques.

The noise factors for the toroid winding process were identified by performing a failure mode effect analysis (FMEA) on the winding process. Ishikawa, as presented in Montgomery [31], suggests four general types of failure mode: man, machine, method, and materials. For the toroid winding process, the noises were identified to be:

Man

experience/skill of the operator

Machine

slop in the core rotation speed setting
position of the shuttle with respect to the toroid during winding

Method

handling of the wound toroids while being transported to the cutting area
handling of the toroids in the cutting area (external to the mechanical transducer production area)
variation in the quality of the cut in the toroid

Materials

variation in the magnetic properties of the magnetic cores
quality of the wire used

In a robustness optimization of a manufacturing process, nearly all the noises seen by the process can be accounted for during experimentation simply by operating under normal factory conditions. For instance, during the toroid winder experiments, no special effort was made to control in any way the handling of the toroids from station to station or the quality of the wire or cores used.

In one case, however, it was desirable to control the noise factor and run a set of replicate experiments. It was discovered that there is a significant amount of slop in the dial which sets the core rotation speed, such that the rotation speed is different when the dial is set from the high side than when set from the low side. Although one method for setting the rotation speed could be specified in the process procedures, it is desirable to make the process robust to either method; because it is such a subtle instruction, it can easily be overlooked.

Identifying the Quality Metric

The most important, and often the most difficult, part of running a designed parametric experiment is to determine what metric will be used to determine the quality of the output of the process. In the case of the toroid winder, this was no different. Two quality metrics were identified.

First, the inductance through the toroid was measured before the operator made any adjustments to try to get the toroid within specifications. Known as "initial inductance," this is a measure of how consistently the toroids could be built prior to adjustment by the operator.

Second, the highest and lowest inductance through the toroid, achieved by adjusting the windings to their extremes, were measured. The second metric, then, was the mean value (called "mean value") between the high and low measurements. This metric is a measure of how consistently the toroids could be built, taking adjustment into account.

In addition to these two continuous variable quantitative metrics, consideration was given to the ease of processing and the minimization of throughput time at the different settings of the control factors. If all other factors were equal, the settings which allowed the easiest processing and the least processing time would be chosen as optimal.

Selecting the Signal to Noise Ratio

The distinction between a designed parametric experiment and a robustness optimization experiment lies in the transformation of the performance metric into a signal-to-noise ratio. This secondary way of evaluating the quality of the toroids is based on the quadratic quality loss function developed by Taguchi [42]. The quality loss function proposes that the added cost to society above the manufacturing price increases as the square of the deviation of the product from its target value. Utilizing the signal-to-noise ratio on the quality metric is a way to ensure that the results of the experiments produce toroids which are consistently close to the target inductance value (both initial inductance and mean value inductance).

Phadke espouses the use of the nominal-the-best signal to noise ratio, which maximizes the ratio of the mean value squared to the variance for a particular experimental run. It is given by the equation:

$$\eta = 10\log_{10}\frac{\mu^2}{\sigma^2}$$

The use of the nominal-the-best S/N ratio is predicated on the existence of an adjustment factor. Maximizing the S/N ratio is equivalent to minimizing the variation about the mean for the experimental run, not about the target value. Once the variation has been minimized relative to the sample mean, an adjustment factor which does not affect the variation is used to shift the mean to its target value.

For the toroid winder experiments, there is a natural adjustment factor: the adjustments to the toroid windings that the operator does when calibrating the toroid. For this reason, the nominal-the-best S/N ratio would appear to be an ideal choice; the minimization of either initial inductance or mean value could be performed, and then the toroids could be adjusted to the target inductance.

There is one problem with using solely the nominal-the-best S/N ratio, however. The amount of adjustment to target that the operators can do is limited. With a target inductance of 171.5 mH, the operators can generally adjust the inductance by approximately +/-15mH. This means that if the minimized variance occurred at mean values higher than 186.5mH or less than 156.5mH, adjustment to target would not be possible.

For this reason, a second S/N ratio was developed and used for these experiments. Designated the mean-squared-deviation-from-target S/N ratio, the ratio is given as:

$$\eta = -10\log_{10} \frac{\sum_{i=1}^{n} (x_i - T)^2}{n}$$

where x_i is the quality metric returned from a single experiment, n is the number of replicates at the experimental setting from which x_i was obtained, and T is the target value. The purpose of using this S/N ratio is strictly to minimize the average squared deviation about the target value.

Both signal-to-noise ratios were calculated, and the results of both were compared and used to determine the optimal settings for the control factors.

For the toroid winder experiments, it was found that using either the nominal-the-best or the mean-squared-deviation-from-target S/N ratio did not have a significant impact on determining the optimal settings. A greater impact was seen when using different metrics, initial inductance or mean value inductance.

Summary of Experiment Preparation

Five control factors have been identified as parameters to vary in the experiments to increase the robustness of the toroids. The levels for these factors have been selected as centered around the existing nominal value and extending above and below the nominal value to near threshold values. The factors and their levels are summarized in Table 1.

Noises which contribute to the variation in toroid quality have also been identified. Most of the noises are environmental or inherent in the manufacturing process, and will be accounted for during the experiments by running the experiments under natural manufacturing conditions. One noise, slop in core rotation can and should be controlled. Each row of the orthogonal array, representing one experimental set-up, will be run at each of two noise levels ("replicates").

Two quality metrics, initial inductance and mean value inductance, were used to gage the quality of the toroids. Two signal-to-noise ratios will be used on each quality metric to transform the quality metric to a measure of robustness.

3.3.3 First Round (L_{18}) Experiments

Selecting the Orthogonal Array

As listed in Table 3.1, there are 5 control factors, varied over 3 levels each. The smallest orthogonal array which can accommodate 5 factors at 3 levels is the L_{18} ($2^1 \times 3^7$), requiring 18 experimental settings.

The next smallest array is the L_9 (3^4), which can accommodate 4 full factors, but which requires only 9 experimental settings. It would have been possible to use the compound factor method described by Phadke [34] to combine two of the 5 factors and allow the use of the L_9 array. However, because the experiments were relatively inexpensive, it was not worth loosing information on the factors to cut down on the number of experiments. The L_{18} was therefore used for the first round of experiments. The experimental set-up for the L_{18} round of experiments is shown in Fig. 3.3.

Selecting the Outer Noise Array

Slop in the core rotation speed setting was the only noise that needed to be controlled. This noise had two possible settings: set from the high side and set from the low side. Each of the 18 experimental settings were, therefore, run four times—twice with the core speed set from the low side, and twice with the core speed set from the high side—requiring 72 experiments in all. Fig. 3.3 shows the inner orthogonal array along with the outer replicates array.

Running the Experiments

72 toroids were wound using the settings and noise levels described above, glued to bases, cut, and measured for initial inductance and high/low inductance. At each stage, the processing of the 72 toroids was randomized, so as to avoid biasing the experimental results.

Four of the toroids did not survive the cutting process; the results for these four toroids had to be omitted from the final calculations.

Expt. #	# Load Winds	Finger Position	Roller Pressure	Core Speed	Wind Speed
1	10	none	-1/8 turn	18	30
2	13	1	-1/8 turn	20	40
3	16	2	-1/8 turn	22	50
4	10	1	nom	20	30
5	13	2	nom	22	40
6	16	none	nom	18	50
7	10	2	+1/8 turn	18	40
8	13	none	+1/8 turn	20	50
9	16	1	+1/8 turn	22	30
10	10	1	-1/8 turn	20	50
11	13	2	-1/8 turn	22	30
12	16	none	-1/8 turn	18	40
13	10	none	nom	18	40
14	13	1	nom	20	50
15	16	2	nom	22	30
16	10	2	+1/8 turn	22	50
17	13	none	+1/8 turn	18	30
18	16	1	+1/8 turn	20	40

Fig. 3.3: Experimental set-up for first round (L_18) of the toroid winding machine robustness optimization experiments

Experimental Results

The initial inductance and high/low inductance measurements for each of the 72 toroids produced (less the 4 lost during cutting) can be seen in Appendix A. Figures 3.4 and 3.5 show the analysis of means (ANOM) and analysis of variance (ANOVA) calculations for the initial inductance metric using both the nominal-the-best and mean-squared-deviation-from-target S/N ratios. Figures 3.6 and 3.7 show the ANOM and ANOVA calculations for the mean value metric using both types of S/N ratios.

The analysis of means is used to determine the main effect of each factor at each of that factor's 3 levels. Due to the way the S/N ratio has been constructed, the optimal setting for each factor is at that level which produces the highest main effect.

The analysis of variance is used to show the importance of each factor in contributing to the robustness of the product (measured by the grand mean). This contribution is measured both relative to the other factors (% contribution), and relative to the noise present in the experiments (F ratio).

Interpretation of the Results

The main effects for each of the factors can be seen in Figs. 3.8 - 3.11. Figures 3.8 and 3.9 show the main effects using the initial inductance metric, transformed by both the nominal-the-best and mean-squared-deviation-from-target S/N ratios, and Figure 3.10 and 3.11 shows the main effects using the mean value metric, also transformed by both S/N ratios. For each factor, the optimal level is the one which yields the greatest main effect. The horizontal lines in each graph shows the grand mean, or average of all the main effects. Therefore, any factor set at a level with a main effect higher than the grand mean, will tend to increase the robustness of the toroids. A summary of the highest main effect for each factor, calculated for the different quality metrics and S/N ratios, can be seen below in Table 3.2.

	Initial Inductance		**Mean Value**	
Factor	**nom-the-best**	**ms dev target**	**nom-the-best**	**ms dev target**
# Load Winds	2	2	2	2
Finger Position	3	3	2	2
Roller Pressure	2	1	2	2
Core Speed	3	2	3	2
Wind Speed	3	3	1	3

Table 3.2: Experimental levels yielding the highest main effect for each of the factors for the first round (L_{18}) of experiments.

Expt#	Noise Levels				
	1st	2nd	3rd	4th	eta
1	205.5	199.7	176.6	176.3	21.87
2	XXXXXX	165.4	173.3	166.0	31.65
3	176.0	179.0	163.7	163.4	26.42
4	193.3	187.7	161.8	180.3	22.39
5	179.4	184.7	162.6	XXXXX	23.65
6	200.4	201.1	180.7	177.7	23.63
7	184.3	170.5	155.5	144.4	19.46
8	195.6	184.7	171.7	177.5	24.97
9	177.8	177.8	155.5	158.6	22.86
10	189.2	193.3	166.8	163.0	21.27
11	180.5	170.7	154.2	XXXXX	22.06
12	202.6	192.4	171.6	181.1	22.84
13	200.3	209.1	181.5	183.4	23.22
14	185.0	185.7	XXXXXX	169.6	25.93
15	164.9	170.4	162.6	158.4	30.32
16	176.3	178.1	164.4	164.3	27.20
17	192.2	184.1	185.9	176.1	28.89
18	168.7	177.1	163.4	154.4	24.83

S/N Ratio: Nominal-the-best | Grand Mean: 24.64

ANOM Calculations

Factor	Level 1	2	3
# Load Winds	22.57	26.19	25.15
Finger Posit	24.24	24.82	24.85
Roller Pressure	24.35	24.86	24.70
Core Speed	22.96	24.38	26.56
Wind Speed	24.73	24.27	24.90

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqrs	Mean Sq	% Contrib	F
# Load Winds	2	41.73	20.86	49.3%	1.5
Finger Posit	2	1.43	0.72	1.7%	0.1
Roller Pressure	2	0.80	0.40	0.9%	0.0
Core Speed	2	39.46	19.73	46.6%	1.5
Wind Speed	2	1.26	0.63	1.5%	0.0
		84.68			
			Error Var		
Error	7	94.30	13.47		
Total SoS	17	178.99			

Fig. 3.4 ANOM and ANOVA calculations for the first round experiments using the initial inductance metric and nominal-the-best S/N ratio.

Expt#	Noise Levels				
	1st	2nd	3rd	4th	eta
1	205.5	199.7	176.6	176.3	-26.99
2	XXXXXX	165.4	173.3	166.0	-13.72
3	176.0	179.0	163.7	163.4	-17.05
4	193.3	187.7	161.8	180.3	-23.57
5	179.4	184.7	162.6	XXXXX	-20.22
6	200.4	201.1	180.7	177.7	-26.61
7	184.3	170.5	155.5	144.4	-24.61
8	195.6	184.7	171.7	177.5	-22.96
9	177.8	177.8	155.5	158.6	-20.98
10	189.2	193.3	166.8	163.0	-23.44
11	180.5	170.7	154.2	XXXXX	-21.04
12	202.6	192.4	171.6	181.1	-25.73
13	200.3	209.1	181.5	183.4	-27.93
14	185.0	185.7	XXXXXX	169.6	-21.11
15	164.9	170.4	162.6	158.4	-18.69
16	176.3	178.1	164.4	164.3	-16.25
17	192.2	184.1	185.9	176.1	-23.10
18	168.7	177.1	163.4	154.4	-19.97

S/N Ratio: Mean sq. dev from target Grand Mean: -21.89

ANOM Calculations

	Level		
Factor	1	2	3
# Load Winds	-23.80	-20.36	-21.51
Finger Posit	-25.55	-20.47	-19.64
Roller Pressure	-21.33	-23.02	-21.31
Core Speed	-23.39	-20.15	-22.12
Wind Speed	-22.39	-22.03	-21.24

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqrs	Mean Sq	% Contrib	F
# Load Winds	2	36.79	18.40	17.7%	2.7
Finger Posit	2	123.00	61.50	59.3%	9.0
Roller Pressure	2	11.59	5.79	5.6%	0.8
Core Speed	2	31.98	15.99	15.4%	2.3
Wind Speed	2	4.18	2.09	2.0%	0.3
		207.55			
			Error Var		
Error	7	47.96	6.85		
Total SoS	17	255.50			

Fig. 3.5 ANOM and ANOVA calculations for the first round experiments using the initial inductance metric and mean-sq.-dev.-from-target S/N ratio.

Expt#	Noise Levels 1st	2nd	3rd	4th	eta
1	189.8	188.5	169.8	172.1	24.63
2	XXXXX	170.5	162.8	164.5	32.30
3	173.1	170.1	158.0	165.9	28.12
4	182.2	174.2	172.8	169.7	30.32
5	171.4	170.9	162.8	XXXXX	30.85
6	185.9	184.6	173.8	171.7	27.81
7	175.5	163.2	156.2	155.4	24.86
8	180.2	173.9	161.8	172.2	27.05
9	165.0	167.4	157.7	158.2	30.45
10	182.8	181.8	163.6	162.1	23.72
11	176.4	167.4	156.8	XXXXX	24.61
12	182.4	176.9	165.8	177.3	28.02
13	188.9	191.8	173.7	176.4	26.16
14	176.0	173.0	XXXXX	167.6	32.19
15	160.8	166.1	163.9	156.9	32.20
16	172.6	172.8	163.6	163.1	29.81
17	182.3	175.6	178.0	171.5	31.82
18	165.3	167.4	164.9	156.5	30.63

S/N Ratio: Nominal-the-best

Grand Mean: 28.64

ANOM Calculations

Factor	Level 1	2	3
# Load Winds	26.58	29.80	29.54
Finger Posit	27.58	29.93	28.41
Roller Pressure	26.90	29.92	29.10
Core Speed	27.45	28.52	29.95
Wind Speed	29.00	28.80	28.12

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqrs	Mean Sq	% Contrib	F
# Load Winds	2	38.35	19.17	36.1%	3.4
Finger Posit	2	17.09	8.55	16.1%	1.5
Roller Pressure	2	29.30	14.65	27.6%	2.6
Core Speed	2	18.88	9.44	17.8%	1.7
Wind Speed	2	2.60	1.30	2.4%	0.2
		106.21			
			Error Var		
Error	7	39.65	5.66		
Total SoS	17	145.86			

Fig. 3.6 ANOM and ANOVA calculations for the first round experiments using the mean value metric and nominal-the-best S/N ratio.

Expt#	Noise Levels				
	1st	2nd	3rd	4th	eta
1	189.8	188.5	169.8	172.1	-21.94
2	XXXXX	170.5	162.8	164.5	-16.25
3	173.1	170.1	158.0	165.9	-17.38
4	182.2	174.2	172.8	169.7	-15.01
5	171.4	170.9	162.8	XXXXX	-14.04
6	185.9	184.6	173.8	171.7	-19.81
7	175.5	163.2	156.2	155.4	-21.61
8	180.2	173.9	161.8	172.2	-16.44
9	165.0	167.4	157.7	158.2	-20.32
10	182.8	181.8	163.6	162.1	-19.82
11	176.4	167.4	156.8	XXXXX	-19.33
12	182.4	176.9	165.8	177.3	-17.24
13	188.9	191.8	173.7	176.4	-22.68
14	176.0	173.0	XXXXX	167.6	-10.92
15	160.8	166.1	163.9	156.9	-20.18
16	172.6	172.8	163.6	163.1	-15.36
17	182.3	175.6	178.0	171.5	-16.43
18	165.3	167.4	164.9	156.5	-19.13

S/N Ratio: Mean sq. dev from target Grand Mean: -17.99

ANOM Calculations

	Level		
Factor	1	2	3
# Load Winds	-19.40	-15.57	-19.01
Finger Posit	-19.09	-16.91	-17.98
Roller Pressure	-18.66	-17.11	-18.21
Core Speed	-18.79	-16.75	-18.44
Wind Speed	-18.87	-18.49	-16.62

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqrs	Mean Sq	% Contrib	F
# Load Winds	2	53.44	26.72	49.9%	3.5
Finger Posit	2	14.30	7.15	13.4%	0.9
Roller Pressure	2	7.66	3.83	7.2%	0.5
Core Speed	2	14.28	7.14	13.3%	0.9
Wind Speed	2	17.37	8.68	16.2%	1.1
		107.05			
			Error Var		
Error	7	53.79	7.68		
Total SoS	17	160.84			

Fig. 3.7 ANOM and ANOVA calculations for the first round experiments using the mean value metric and mean-sq.-dev.-from-target S/N ratio.

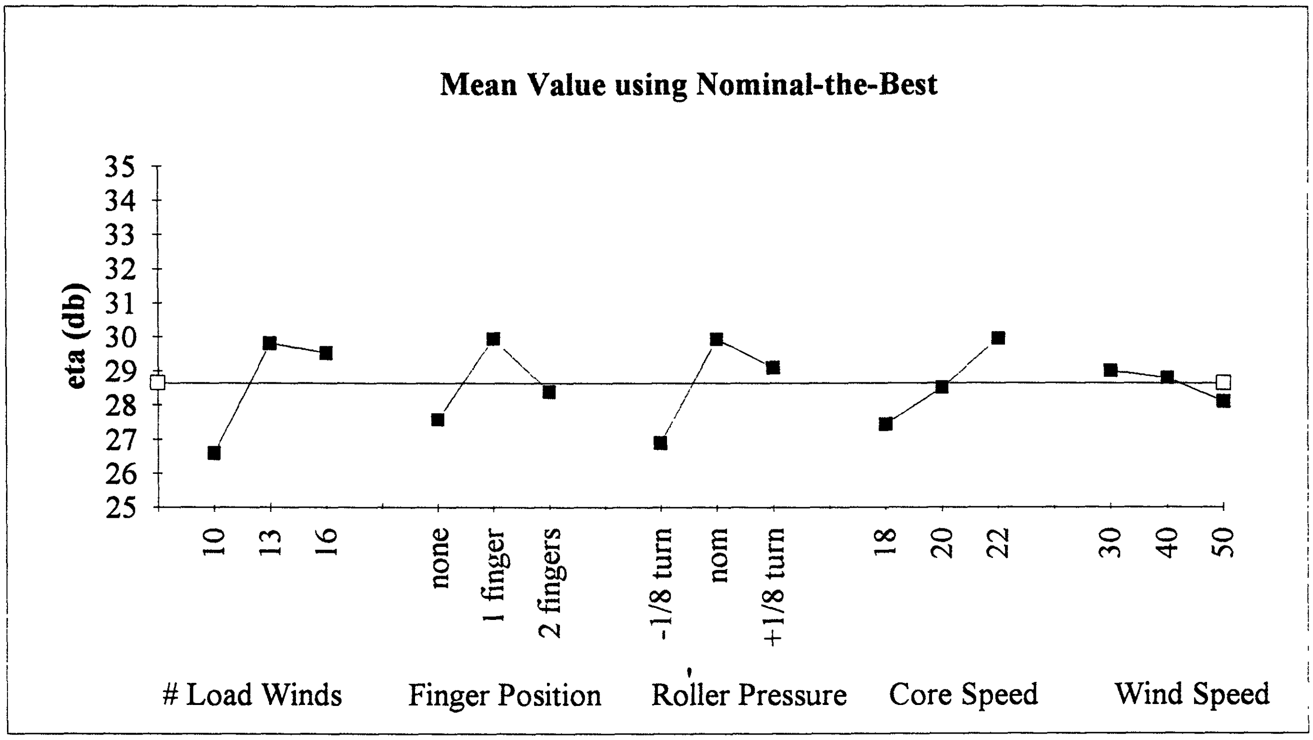


Fig. 3.10 Factor main effects for first round experiments using the mean value metric with the nominal-the-best S/N ratio.

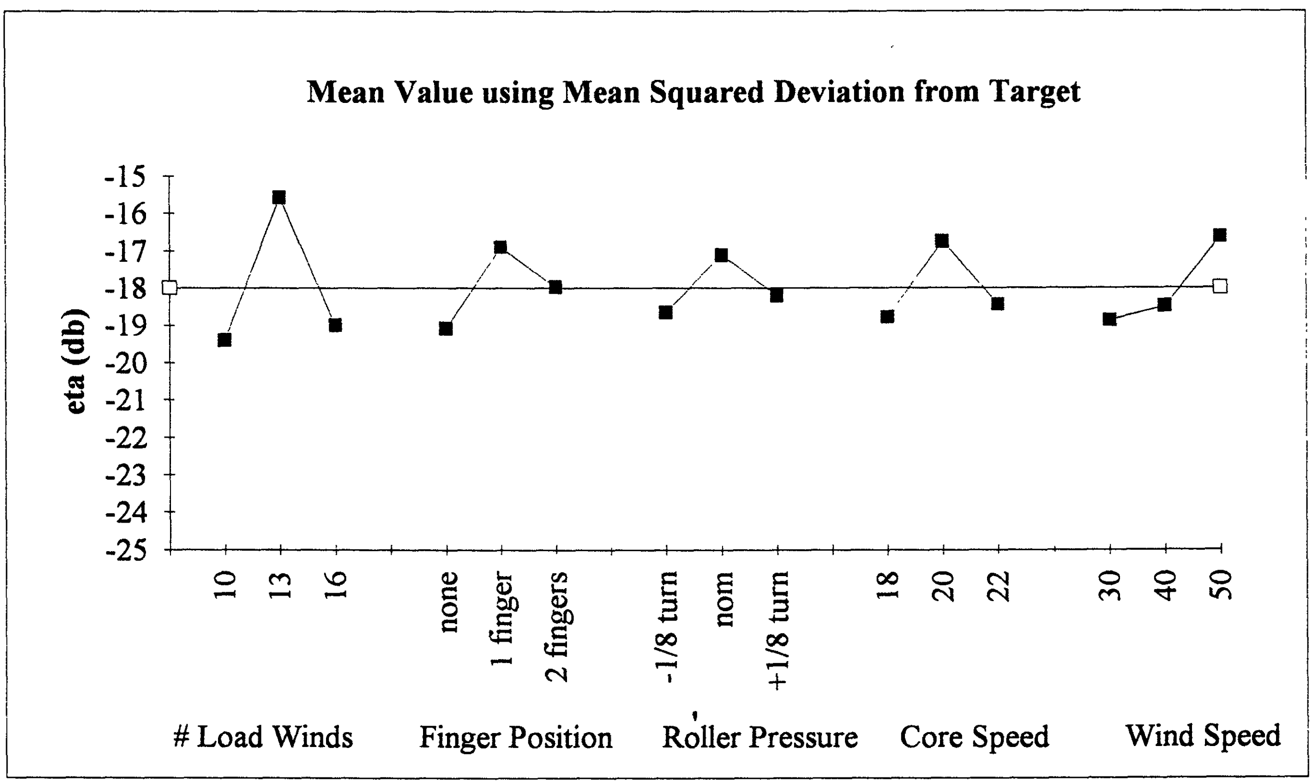


Fig. 3.11 Factor main effects for first round experiments using the mean value metric with the mean-sq.-dev-from-target S/N ratio.

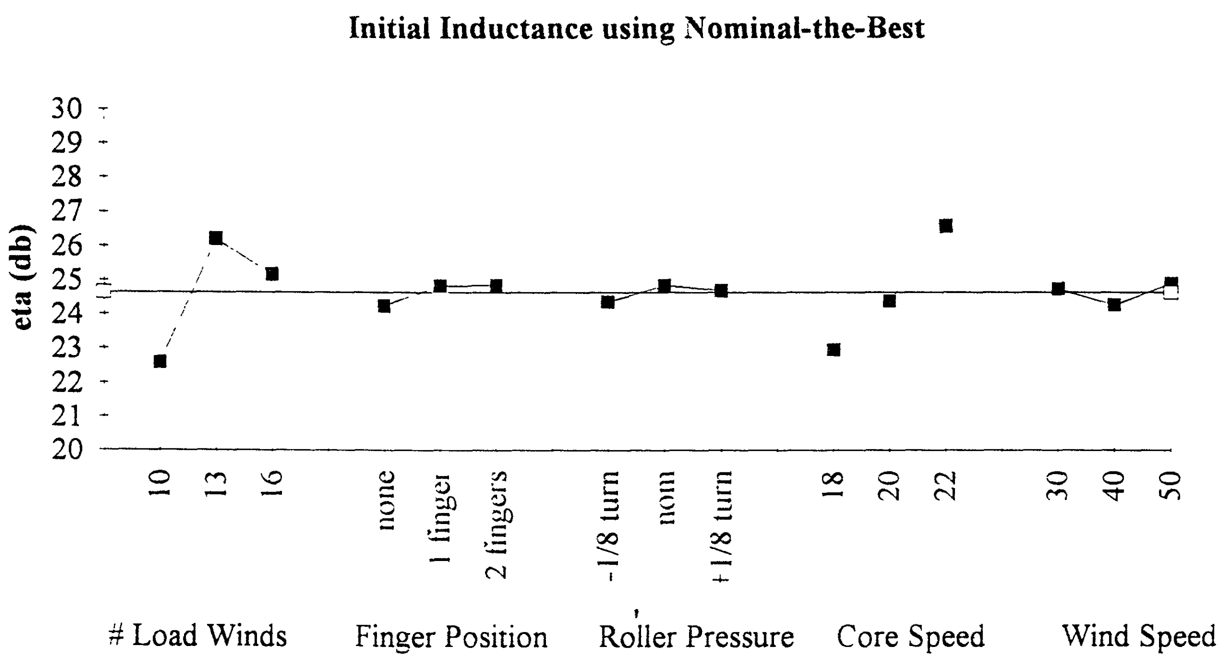


Fig. 3.8 Factor main effects for first round experiments using the initial inductance metric with the nominal-the-best S/N ratio.

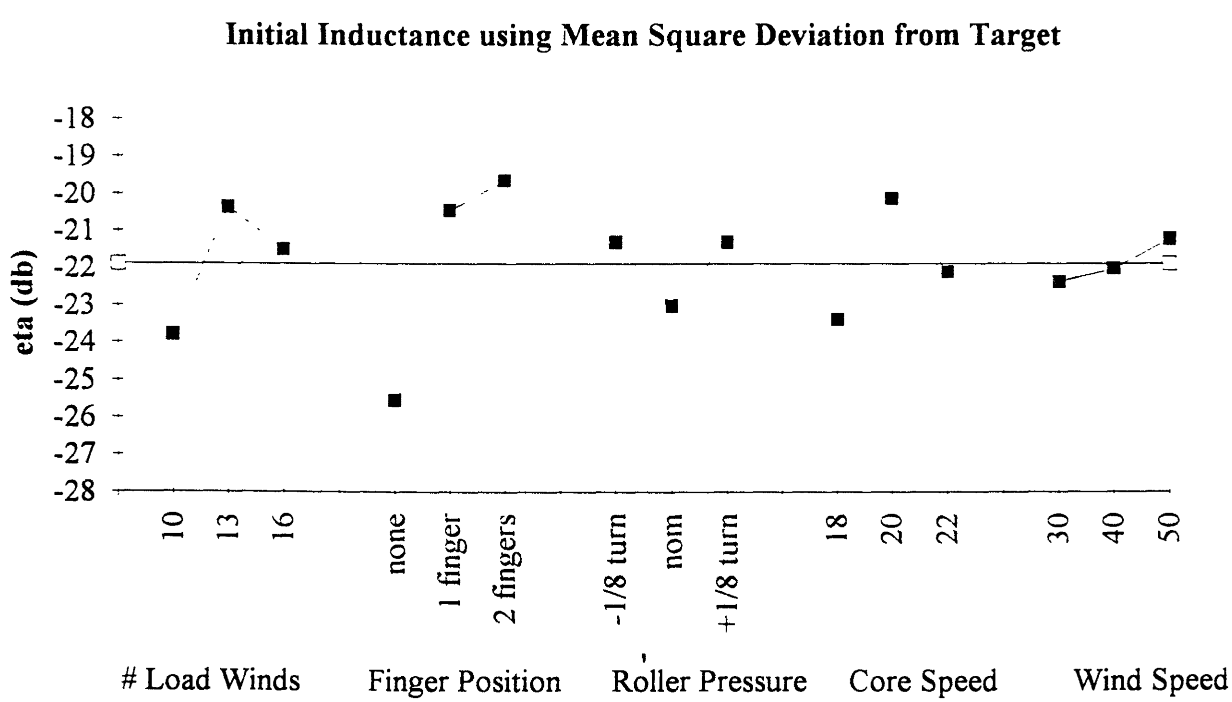


Fig. 3.9 Factor main effects for first round experiments using the initial inductance metric with the mean-sq.-dev-from-target S/N ratio.

For the factor, # Load Winds, both of the quality metrics evaluated at both S/N ratios indicate that the optimal setting is at level 2, the nominal level of 13 winds. There is strong evidence in each factor effect graph that this is the optimal level. No clarification was required for this factor by including it in a second set of experiments.

For the factor, wind speed, the evidence is also considerable that the optimal setting for this factor should be at level 3, or at a wind speed of 50. However, in performing the experiments, the operators encountered difficulty in keeping the wire on the shuttle at this high wind speed. Although the wind speed set at 50 produced the most robust toroids, a setting was sought which would also allow for ease of operation of the toroid winder. Because the mean value metric evaluated with the nominal-the-best S/N ration indicated an optimal at level 1, the second round of experiments had to test both above and below the nominal value of 40. The settings for the second round of experiments were then chosen to be: 35, 40, and 45.

Similarly, for the factor, roller pressure, the results of the factor effects calculations suggest that level 2 is the optimal. However, the evidently minimizing performance of level 2 for the mean value metric using mean squared deviation from target, the poor performance of level 1 at the other metrics, and operator difficulty using the low levels of roller pressure, indicated that the second round of experiments should be conducted at levels between 2 and 3. The settings for the second round of experiments for this factor were then chosen to be: nominal, +1/16 turn, and +1/8 turn.

For the factors, core speed and finger position, the use of different metrics and different S/N ratios resulted in different indications as to the optimal settings for the factors. For clarification, both factors would be run in the second set of experiments at levels between 2 and 3. The settings for core speed were: 20, 21, 22; the settings for finger position were: 1 finger and 2 fingers.

3.3.4 Second Round (L_9) Experiments

Because the optimal settings for some of the factors from the first set of experiments had not been conclusively determined, it was decided to run further experiments. This was a bit of a luxury, but considering that the experiments were relatively inexpensive to run, the extra clarification obtained from extra experiments clearly outweighed the added cost.

Experimental Set-up

The results of the first round of experiments were presented in Figs. 3.4 - 3.11, summarized in Table 3.2 and interpreted in the final subsection of section 3.3.3. Table 3.3 shows the factors to be evaluated in the second round of experiments and their experimental levels.

Factor	Lo	Middle	Hi
Finger Position	1 finger	2 fingers	--
Roller Pressure	nominal	+1/16	+1/8
Core Speed	20	21	22
Wind Speed	35	40	45

Table 3.3: Factors and experimental levels used in the second round (L_9) of experiments.

Table 3.3 indicates that there are four factors to be used in the experiments, 3 factors at 3 levels each and 1 factor at 2 levels. Using the dummy level technique described in Phadke [34], the fourth column of an L_9 orthogonal array was transformed from a three-factor three-experiments each column to a two-level column with 3 experiments at level 1 and 6 experiments at level 2. With this transformation, the second round of experiments was performed using a L_9 orthogonal array. The experimental set-up is shown in Fig. 3.12. The outer noise array consists of three replicate experiments for each level of the orthogonal array, two coming from the low end of the core speed dial, and one from the high side.

Running the Experiments

A similar experimental procedure was used for the second round of experiments as was used for the first. 27 toroids (9 experimental levels at 3 replicates each) were wound on the toroid winder using the experimental settings outlined in Fig. 11, glued to bases, cut, and measured for initial inductance and high/low inductance. Once again, at each stage, the processing of the 27 toroids was randomized, so as to avoid biasing the experimental results.

Experimental Results

The initial inductance and high/low inductance measurements for each of the 27 toroids produced can be seen in Appendix A. Figures 3.13 and 3.14 show the ANOM and ANOVA calculations for the initial inductance metric using each of the S/N ratios, and Figures 3.15 and 3.16 show the ANOM and ANOVA calculations for the mean value metric using each of the S/N ratios.

The main effects for each of the factors in the second round of experiments can be seen graphically in Figs. 3.17 - 3.20. A summary of the results of the main effect calculations can be seen in Table 3.4 below.

Expt#	Roller Pressure	Core Speed	Wind Speed	Finger Position
1	Nom	20	35	2
2	Nom	21	40	1
3	Nom	22	45	2
4	+1/16	20	40	2
5	+1/16	21	45	2
6	+1/16	22	35	1
7	+1/8	20	45	1
8	+1/8	21	35	2
9	+1/8	22	40	2

Fig. 3.12: Experimental set-up for second round (L_9) of the toroid winding machine robustness optimization experiments.

Expt#	1st	2nd	3rd	eta BP
1	192.5	192.1	166.5	21.82
2	180.0	187.3	162.5	22.83
3	166.6	172.6	154.2	24.87
4	186.6	181.6	153.9	19.90
5	189.4	183.5	158.2	20.57
6	166.3	176.5	160.0	26.08
7	183.1	187.7	169.0	25.33
8	180.2	170.1	160.8	24.87
9	181.9	163.0	161.7	23.48

Grand Mean: 23.31

ANOM Calculations

	Level		
Factor	1	2	3
Roller Pressure	23.18	22.18	24.56
Core Speed	22.35	22.76	24.81
Wind Speed	24.25	22.07	23.59
Finger Position	24.75	22.59	

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqr	Mean Sq	% Contrib.	F
Roller Pressure	2	8.56	4.28	23.9%	1.82
Core Speed	2	10.46	5.23	29.2%	2.22
Wind Speed	2	7.52	3.76	21.0%	1.60
Finger Position	2	9.33	4.67	26.0%	1.98
		35.87			
Error		2.36			
Total		38.23			

Fig. 3.13 ANOM and ANOVA calculations for the second round of experiments using the initial inductance metric and nominal-the-best S/N ratio.

Expt. #	1st	2nd	3rd	eta BP
1	192.5	192.1	166.5	-24.72
2	180.0	187.3	162.5	-21.28
3	166.6	172.6	154.2	-20.34
4	186.6	181.6	153.9	-23.14
5	189.4	183.5	158.2	-23.30
6	166.3	176.5	160.0	-17.88
7	183.1	187.7	169.0	-21.28
8	180.2	170.1	160.8	-18.09
9	181.9	163.0	161.7	-19.64

Grand Mean -21.08

ANOM Calculations

	Level		
Factor	1	2	3
Roller Pressure	-22.12	-21.44	-19.67
Core Speed	-23.05	-20.89	-19.29
Wind Speed	-20.23	-21.35	-21.64
Finger Position	-20.15	-21.54	

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqr	Mean Sq	% Contrib.	F
Roller Pressure	2	9.54	4.77	25.1%	0.77
Core Speed	2	21.35	10.67	56.1%	1.72
Wind Speed	2	3.33	1.66	8.7%	0.27
Finger Position	2	3.86	1.93	10.1%	0.31
		38.08			
Error		6.21			
Total		44.28			

Fig. 3.14 ANOM and ANOVA calculations for the second round of experiments using the initial inductance metric and mean-sq.-dev-from-target S/N ratio.

Expt#	1st	2nd	3rd	eta BP
1	179.0	178.7	167.0	28.13
2	171.6	175.5	165.3	30.46
3	165.3	167.3	158.1	30.63
4	178.3	168.7	154.1	22.72
5	173.5	176.0	157.3	24.42
6	163.9	172.7	159.1	27.56
7	174.5	175.8	172.6	40.67
8	174.1	165.3	161.0	27.95
9	176.4	168.0	154.8	23.66

Grand Mean: 28.47

ANOM Calculations

Factor	Level 1	Level 2	Level 3
Roller Pressure	29.74	24.90	30.76
Core Speed	30.51	27.61	27.28
Wind Speed	27.88	25.62	31.91
Finger Position	32.90	26.25	

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqrs	Mean Sq	% Contrib	F
Roller Pressure	2	58.81	29.41	25.9%	0.12
Core Speed	2	18.89	9.45	8.3%	0.04
Wind Speed	2	60.96	30.48	26.9%	0.12
Finger Position	2	88.35	44.17	38.9%	0.18
		227.02			
Error		244.10			
Total		471.12			

Fig. 3-15 ANOM and ANOVA calculations for the second round of experiments using the mean value metric and nominal-the-best S/N ratio.

Expt#	1st	2nd	3rd	eta BP
1	179.0	178.7	167.0	-16.30
2	171.6	175.5	165.3	-12.56
3	165.3	167.3	158.1	-18.97
4	178.3	168.7	154.1	-21.94
5	173.5	176.0	157.3	-18.77
6	163.9	172.7	159.1	-18.54
7	174.5	175.8	172.6	-9.73
8	174.1	165.3	161.0	-17.16
9	176.4	168.0	154.8	-20.24

Grand Mean: -17.13

ANOM Calculations

Factor	Level 1	2	3
Roller Pressure	-15.94	-19.75	-15.71
Core Speed	-15.99	-16.16	-19.25
Wind Speed	-17.33	-18.24	-15.82
Finger Position	-13.61	-18.90	

ANOVA Calculations

Factor	Deg Frdm	Sum of Sqrs	Mean Sq	% Contrib.	F
Roller Pressure	2	30.83	15.42	26.6%	12.20
Core Speed	2	20.21	10.10	17.4%	8.00
Wind Speed	2	8.99	4.49	7.7%	3.56
Finger Position	2	55.96	27.98	48.2%	22.15
		115.99			
Error		1.26			
Total		117.26			

Fig. 3-16 ANOM and ANOVA calculations for the second round of experiments using the mean value metric and mean-sq.-dev-from-target S/N ratio.

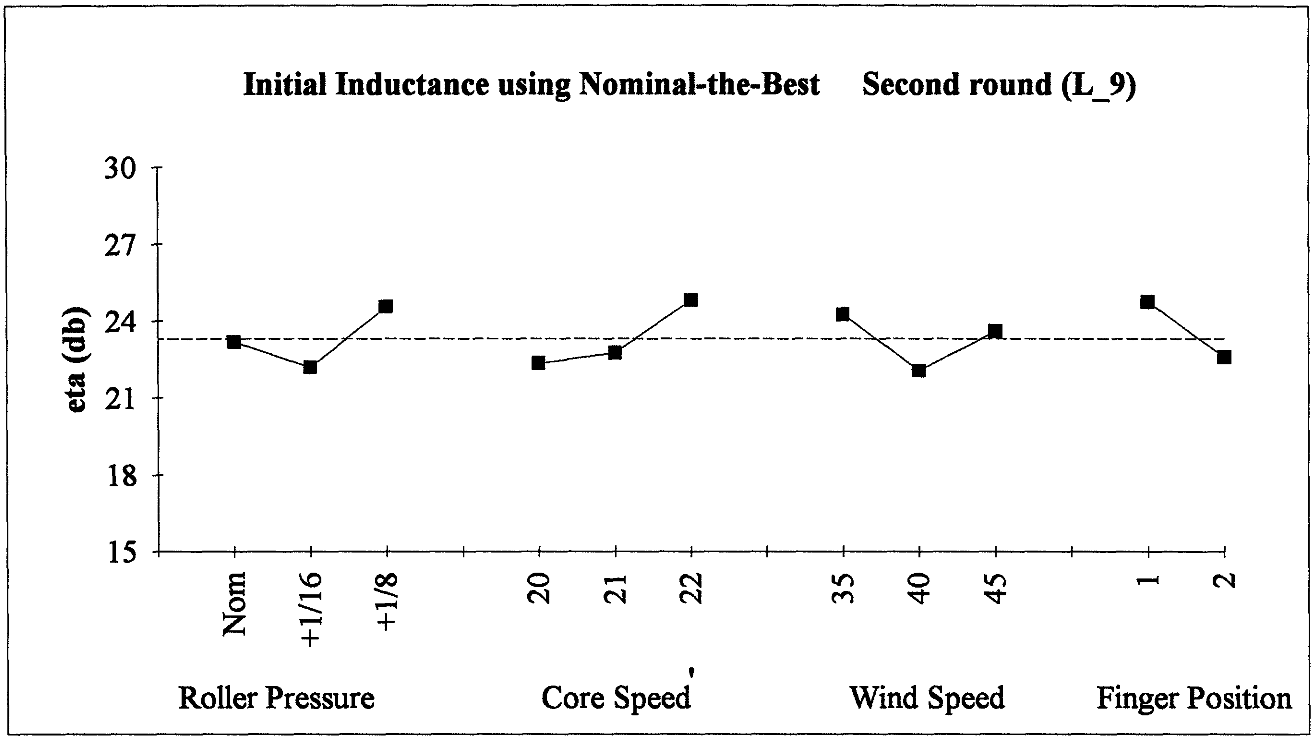


Fig. 3.17 Factor main effects for the second round of experiments using the initial inductance metric and the nominal-the-best S/N ratio.

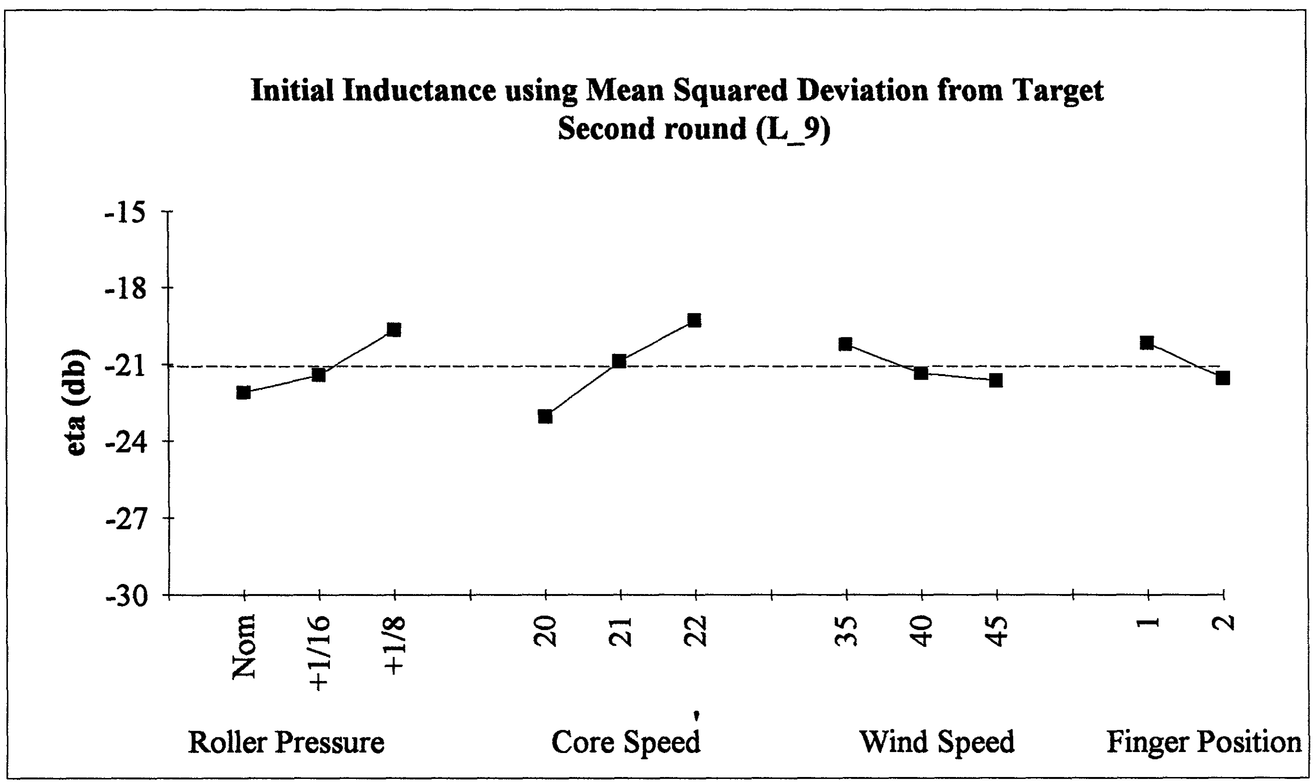


Fig. 3.18 Factor main effects for the second round of experiments using the initial inductance metric and the mean-sq.-dev-from-target S/N ratio.

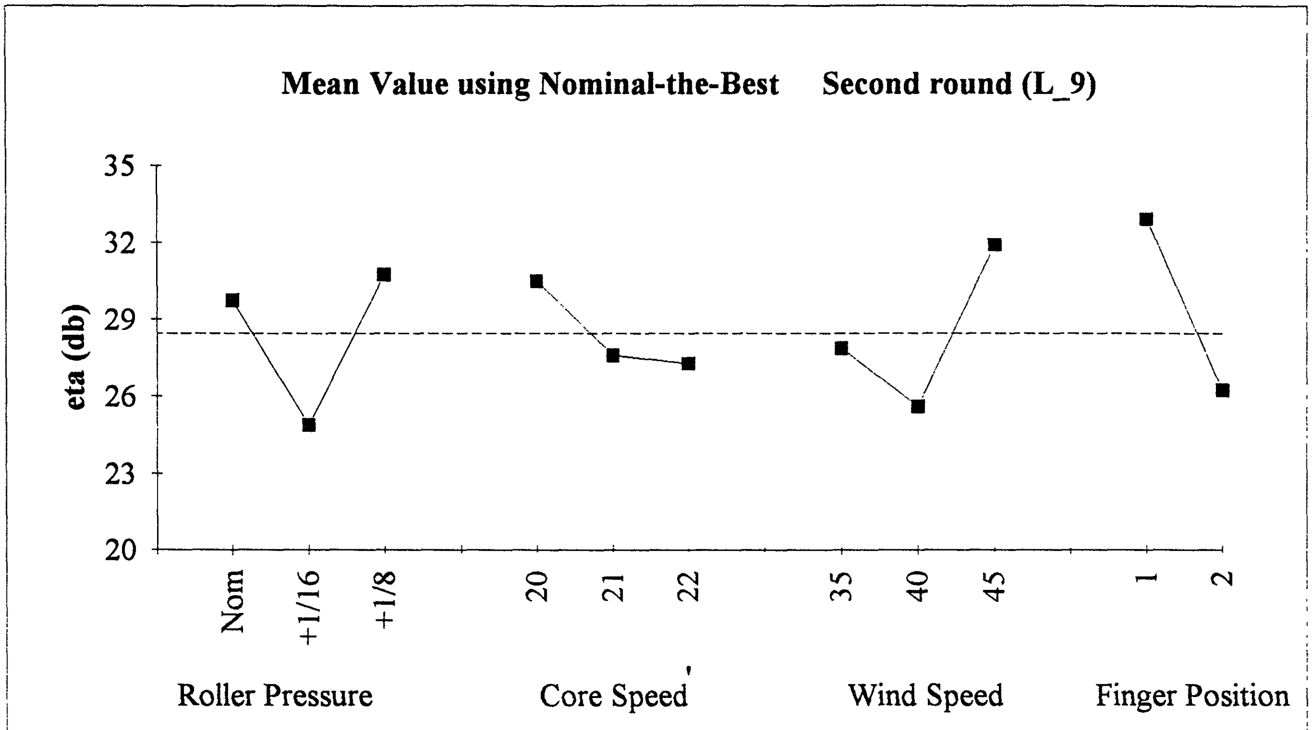


Fig. 3.19 Factor main effects for the second round of experiments using the mean value metric and the nominal-the-best S/N ratio.

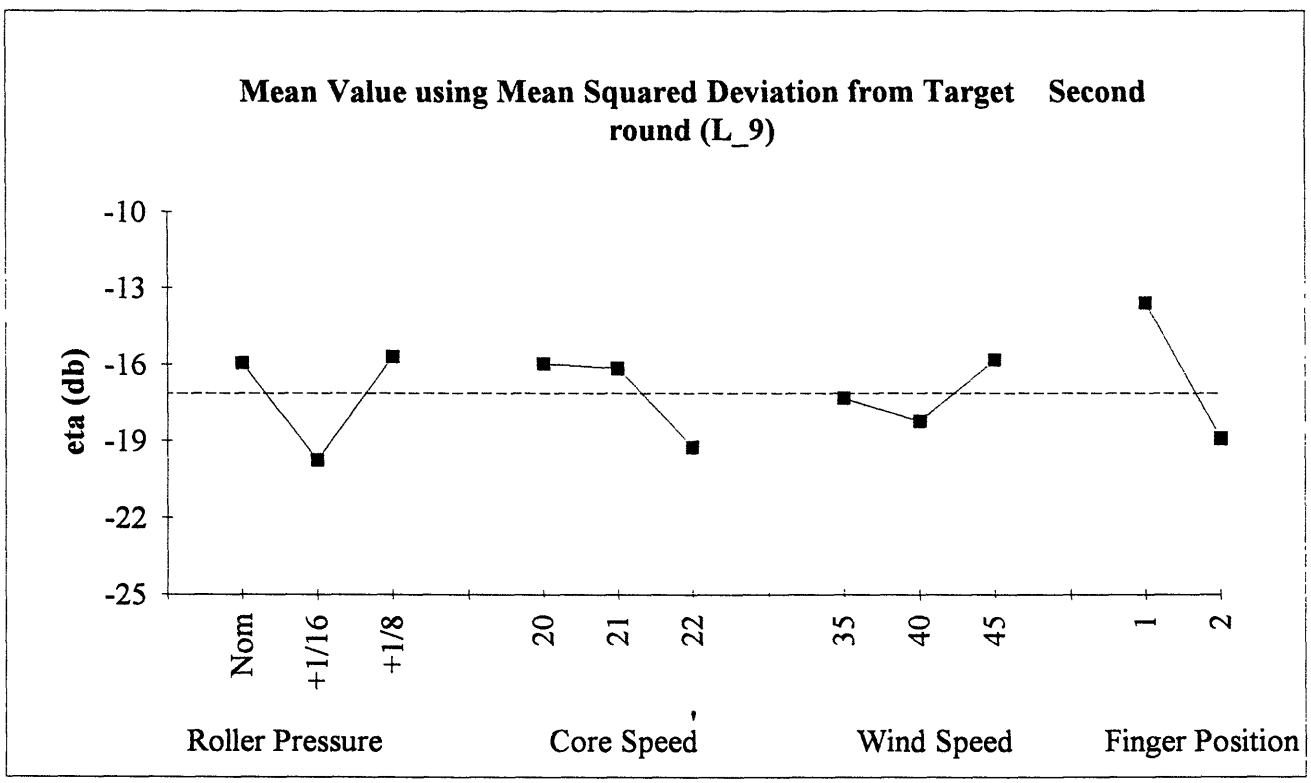


Fig. 3.20 Factor main effects for the second round of experiments using the mean value metric and the mean-sq.-dev-from-target S/N ratio.

	Initial Inductance		Mean Value	
Factor	**nom-the-best**	**ms dev target**	**nom-the-best**	**ms dev target**
Finger Position	1	1	1	1
Roller Pressure	3	3	3	3
Core Speed	3	3	1	1
Wind Speed	1	1	3	3

Table 3.4: Experimental levels yielding the highest main effect for each of the factors for the second round (L_9) of experiments.

For the factors, finger position and roller pressure, the results of the second round of experiments are unanimous across the different quality metrics and S/N ratios. The optimal setting for finger position was level 1, requiring the use of 1 finger to guide the wire as it is loaded onto the winding shuttle. The optimal setting for roller pressure was level 3, requiring an increase in roller pressure by +1/8 turn on the spring-loaded pressure tensioner.

For the factors, wind speed and core speed, the optimal settings are not as obvious. The use of a different quality metric affects which setting will be chosen as optimal. In this case, secondary factors were taken into consideration. For wind speed, it is noted that setting the wind speed at 45, level 3, as opposed to 35, level 1 decreases the time necessary to complete the toroid winding operation, thereby increasing throughput. Moreover, choosing speed 45 over speed 35 is a more conservative choice. The overall net effect of selecting 45 as the optimal setting can be computed by subtracting the main effect of the wind speed factor at level 3 from the grand mean computed for a given quality metric evaluated at a given S/N ratio. As such, the net effect of setting wind speed to 45 can be computed to be:

$$\begin{gathered}\textit{net effect} = \\ (23.59 - 23.31) + (-21.64 - (-21.08)) + (31.91 - 28.47) + (-15.82 - (-17.13)) = 4.47\,dB\end{gathered}$$

Similarly, the net effect of setting wind speed to 35 can be computed to be:

$$\begin{gathered}\textit{net effect} = \\ (24.25 - 23.31) + (-20.23 - (-21.08)) + (27.88 - 28.47) + (-17.33 - (-17.13)) = 1.00\,dB\end{gathered}$$

meaning that setting the wind speed to 45 is more robust to each type of quality metric and S/N ratio by 3.47dB over setting the wind speed to 35. For these two reasons, the optimal setting for the wind speed factor was determined to be 45.

For core speed, the raw experimental data was examined, as shown in Appendix A. There is a target inductance for the toroids, with specification limits around that target inductance.

From the hi/lo inductance measurements, it is obvious that some of the toroids produced could not be adjusted to within specs; for example, the third replicates of experiments 4, 5, 6, 8, and 9. Also, the third replicates of experiments 2 and 3 are only narrowly within the specs. Referring to Fig. 3.12, we see that these experiments (with the exception of number 4) took place at level 2 and 3 of the core speed setting. It is, therefore, more conservative and more robust to set the optimal level of core speed to 20.

It is noted also that these toroid failures all occurred on the third replicate, where the core speed was set from the high side. It was recommended, therefore, that the official process procedures, which contain the instructions for the toroid winding process, instruct the operators to set the core speed from the low side. These experiments have been conducted to ensure that the toroids built are robust to setting core speed from either side, but the best toroids will be built if core speed is set from the low side.

The optimized toroid winding machine settings are summarized in Table 3.5 below:

Factor	**Optimized Setting**
# Load Winds	13
Finger Position	1
Roller Pressure	+1/8 turn
Core Speed	20
Wind Speed	45

Table 3.5: Optimized toroid winding machine settings as determined by two rounds of robustness optimization experiments.

IV. Data-Driven Process Control Scheme

This chapter describes the data-driven process control scheme which was implemented on the mechanical transducer production line at Company X. Because the line is primarily a hand-assembly operation, continuous variable quality metrics were difficult to obtain for most of the process. In this case, data collection sheets have been created to provide the feedback to the engineers about the health of the process. Because the low production volumes make rigid statistical analysis of this information difficult, the data is analyzed once a week on a 30-day moving window scale.

Three different methods of process control are described. First is the work of the Corrective Action Team on the mechanical transducer production line. The team was established just prior to the beginning of this research, and its primary function is to provide the engineering support to the line during out-of-control process conditions. Second is the establishment of a data collection system through check sheets which the assemblers fill out as a means of obtaining a metric to gage the quality of the process output and the health of the process. Third is the use of CUSUM statistical process control to monitor the tank test, one of the only parts of the line in which continuous variable quality measurements are taken.

4.1 The Corrective Action Team

The Corrective Action Team was established just prior to the commencement of the work for this thesis. The team consists of: the line supervisor, an electrical engineer and a mechanical engineer who support the line, and also an engineer responsible for data collection. There are no full-time representatives on the team from R&D or from among the production assemblers, but these people are at times invited to bring their expertise to a particular meeting. The team meets once each month to analyze the productivity for the past month, define issues which require extensive engineering attention, and propose short- and long-term courses of action.

At the start of the program, the only metric which the CAT analyzed was first pass yield percentage. This number represents the number of transducers which passed each of the four final tests on the first try (i.e. no rework required) divided by the total number of transducers built that month. Although a good starting point, first pass yield percentage is very limited in the amount of useful information it conveys to the team. For one, it does not take into account the effect that a transducer which is built, tested, fixed, and retested several times has on the efficiency of the line. This effect can be devastating because often it takes as much time to break down a transducer for repair as it does to build one. Several transducers can be assembled in the time it takes to build, test, fix, and retest one.

Moreover, the first pass yield metric does not allow any insights into what part of the process is experiencing difficulties. Because it is measured only at final test, it can account for only those problems which become apparent at that final stage of production. It does not indicate any difficulties which may be occurring, and then remedied through rework, at the sub-assembly stages of production.

This lack of data about the process was the motivation for this thesis work. The Corrective Action Team wanted to have access to information which would provide it with a knowledge of how the entire line is performing. The team needs to rapidly identify problems on the line, and be able to quickly diagnose the root cause of the problem, so as to be able to efficiently allocate engineering resources to the line.

Using the data collection system described below, the team now receives reports from several different locations on the line. In addition, it has access to data collection sheets from several other locations on the line for the purpose of diagnosing the root cause of any problem on the line. In the future, it will also receive monthly updates of the CUSUM charts used to detect drifts in the tank test.

4.2 Data Collection Sheets

The lack of quality metrics on a hand assembly production line made it necessary to develop alternative means for gaging the health of the process and acquiring feedback on how various factors were affecting the production line. Check sheets were developed for the operators to fill out, much in the same way that data is plotted by the operators on control charts when traditional SPC is used.

In this case, however, the operators merely collect the data, and it is the engineer supporting the line who is responsible for analyzing and interpreting the information. It is generally preferable for the operators working the production line to perform at least minimal analyses on the data they collect. It is believed [10, 31] that this empowers the line to seek solutions to problems which they are better qualified to solve than engineers because of their closer involvement in collecting the data and running the process.

On the mechanical transducer line, the notion of data collection as a means of process control is still relatively new, and it was believed that the responsibility for both collecting and processing the data was too great for the operators at this time. Future plans for the data collection have the operators directly inputing the information into computers (for easy processing and storage), analyzing the resultant graphs and charts, and taking appropriate corrective action when necessary.

Indeed, it was not always easy to get the operators to collect the data in the first place. Throughout the process of implementing the use of these data sheets, several important lessons were learned about implementing any data-driven process control scheme.

First, it is important that the sheets are easy for the operators to understand. If there is any confusion about what type of information is required on the data sheet, frustration, both on the part of the engineer and the operator, will result. The sheets should be written in the parlance that the operators themselves use when referring to the process or product. For instance, on many of the sheets, the word "flavor" is used as a substitute for "model type," because this is the term that is used commonly around the plant and on the mechanical transducer line.

Second, the operator will take "ownership" of the sheet, and therefore provide the best information, if he can see the need for developing a sheet "independent" of the engineer. In this case, the engineer approaches the assembler with the intent of creating a data collection sheet, but rather than imposing it upon the assembler, leads the assembler through an exercise in which the assembler suggests that certain information be recorded.

Third, the best successes on the mechanical transducer line came following emergencies on the line. During an out-of-control situation, when the output of the line is in jeopardy, the operators are quite willing to record any information which will help the engineer solve the problem. If this means is successful, then it is easy to convince the line that the information is valuable enough to want to collect on a continual basis.

Below is a description of all of the data collection sheets, how each one is used, and the way that the sheets are processed and analyzed.

4.2.1 Data Collection at Final Test

An example of the data sheet created to monitor Model A production at final test can be seen in Fig. 4.1. The four tests done on the transducer prior to shipping–hi pot, tank, image, and hitting cap–provide the best insight into the health of the process, because they are the operation which is furthest downstream in the production process. In analyzing these tests, it was necessary to avoid the pitfalls originally experienced by the CAT when the team was analyzing merely first pass yield at final test.

For this reason, every test performed is recorded, not just the first pass following production. The yield number that results is the number of successful battery of tests divided by the number of tests performed. This yield number, then, accounts for those transducers which fail at final test and are then reworked and tested again. Furthermore, by including marketing and customer exchange models on the sheet (but not in the calculations), possible failures to the test equipment can also be monitored.

It is desired to have a rapid response to authentic out-of-control situations. This requires both a quick detection method and a means for distinguishing between an out-of-control situation and a false alarm. To ensure quick detection of problems, these sheets are collected and analyzed once a week (the low volumes have dictated this time period which, on most other production lines would be an eternity). Because one week is too short a period to determine the validity of an out-of-control situation, however, the data is analyzed based on the prior 30 days of activity. This 30-day moving window is an effective way to view the data and make valid judgements on the corrective action to take.

Model A Final Test Data Sheet

Date	S/N	Flavor	Source	Test Failed: HiPot	Tank	Image	Jitter	Hit Cap	Noise	Cosmetic
EXAMPLE	*serial #*		*circle one*	*leak location*	*circle one*	*what failed*				*what failed*
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					
			P M CE		IL VPP Other					

Fig 4.1 Example of data collection sheet for Model A at final test.

Final Test 30-Day Window Report

Feb 4 - March 4

Pass:	xxx
Test:	xxx
Pct:	83.7%

Failure	#
Tank	x
Noise	x
Image	x
Cosmet	x
Total	x

Failure Mode Breakdown

Image: x) Line pairs

Tank: x) no ultrasound
x) IL
x) Lateral

Noise: x) motor

Cosmetic: x) Scratched cap
x) Damaged cable

Feb 11 - March 11

Pass:	xxx
Test:	xxx
Pct:	82.6%

Failure	#
Tank	x
Noise	x
Image	x
Total	x

Failure Mode Breakdown

Image: x) B-side dead

Tank: x) no ultrasound
x) IL

Noise: x) motor

Feb 18 - March 18

Pass:	xxx
Test:	xxx
Pct:	88.3%

Failure	#
Tank	x
Noise	x
Total	x

Failure Mode Breakdown

Tank: x) no ultrasound
x) IL
x) VPP
x) Lateral
x) Ctr. freq.

Noise: x) motor

Feb 25 - March 25

Pass:	xxx
Test:	xxx
Pct:	88.4%

Failure	#
Tank	x
Total	x

Failure Mode Breakdown

Tank: x) no ultrasound
x) IL
x) VPP
x) Lateral
x) Focal pt.
x) Not op.

Fig. 4.2 Example of 4 weeks of 30-day moving window reports based on data from Model A at final test.

Figure 4.2 shows an example of four consecutive weeks of these 30-day moving window reports for the final test. For each week, the following are presented: a final test yield percentage, the number of each of the four tests that was failed, and a breakdown of these failures by root cause. In a glance, these reports indicate how process is doing and what, if anything, is wrong with it.

4.2.2 Data Collection at Final Assembly

A similar approach was taken for monitoring the process at final assembly (sometimes called "cable attach"), the process immediately upstream of the final test process. An example of the data collection sheet at final assembly can be seen in Figure 4.3.

Because diagnostic tests are run on the probe following final assembly, but before final test, these tests are all listed on the data collection sheet, and the operator can easily identify each failure mode. The operator also indicates whether the probe is a first time production unit or a reworked unit (failed a test previously). This is done so that those probes which habitually fall into the build, test, rework cycle can be easily identified.

For the same reasons as above, the data at final assembly is reported each week in a 30-day moving window format. An example of 4 consecutive weeks of 30-day moving window reports is shown in Fig. 4.4. Again, a yield number is presented, indicating the number of tests passed divided by the number of tests performed. The number of each test which was failed is also given, along with a failure mode breakdown to aid the engineer in identifying root causes of problems.

4.2.3 Data Collection at Main Assembly

An example of the data collection sheet used at main assembly can be seen in Figure 4.5. For the main assembly process, immediately upstream of final assembly, there are no diagnostic tests which are performed on the transducer to gage manufactured quality, yet the process is perhaps the most critical one to the successful production of a mechanical transducer.

In this case, the operator fills out a sheet not for each transducer, but rather for only those in which there was some problem. If it is a production unit, then "problem with" could indicate unusual difficulty fitting a part into place, a defective sub-assembly, or problems calibrating the toroid/fin system. If it is a reworked unit, the operator at main assembly indicates what part needed to be changed or adjusted in order to allow the transducer to pass the tests and be shipped.

Statistics and reports are generated for main assembly only on a need basis. This means of data collection is intended for diagnostic uses to aid the engineer in pinpointing the root cause of a problem after one has been identified using the 30-day moving window techniques.

Model A Final Assembly Data Sheet

				Test Failures							
			Prod.	Bubble Test		EEPROM Burn	System Check			Run-In
Date	S/N	Flavor	or Rework	Cable	Lock Ring	EEPROM	No U-sound	Probe Dead	Noise	Cable
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							
			P R							

Fig. 4.3 Example of data collection sheet for Model A at final assembly (cable attach)

Final Assembly 30-Day Window Report

Feb 4 - March 4

Pass:	xxx
Test:	xxx
Pct:	95.0%

Test	# Failures
System:	x
Bubble	x
Total:	x

Failure Mode Breakdown	
System:	probe x not op x
Bubble	cable x

Feb 11 - March 11

Pass:	xxx
Test:	xxx
Pct:	96.2%

Test	# Failures
System:	x
Bubble	x
Total:	x

Failure Mode Breakdown	
System:	not op x
Bubble	cable x

Feb 18 - March 18

Pass:	xxx
Test:	xxx
Pct:	95.3%

Test	# Failures
System:	x
Bubble	x
Total:	x

Failure Mode Breakdown	
System:	not op x
Bubble	cable x

Feb 25 - March 25

Pass:	xxx
Test:	xxx
Pct:	97.0%

Test	# Failures
Bubble	x
Total:	x

Failure Mode Breakdown	
Bubble	cable x

Fig. 4.4 Example of 4 weeks of 30-day moving window reports based on data from Model A at final assembly (cable attach).

Model A Main Assembly Data Sheet

Date	S/N	Flavor	Prod. or Rework	Problem With: Shaft-Spr	Sensor	Motor	Torroid	Cap	Jitter	Top End	PC Board	Other
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									
			P R									

Fig. 4.5 Example of data collection sheet for Model A at main assembly.

4.2.4 Data Collection at Cable Assembly

An example of the data collection sheet used at cable assembly can be seen in Figure 4.6. This data collection sheet is a combination of those used at main assembly and at final assembly. Like main assembly, this sheet is intended primarily for diagnostic uses, and, therefore, requires that the operator fill it out only if a problem is encountered with a cable sub-assembly. Nevertheless, it is very useful for isolating problems which stem from lack of electrical conductivity between the system and the transducer.

Similar to the sheet used in main assembly, however, is the fact that there are tests which the operator can perform to understand the nature of the failure that has been encountered. It is therefore a straightforward translation from diagnosis of failure to entering the data on the collection sheet.

If the cable has been rejected and is coming back to the cable assembly station for rework, the operator is instructed to indicate the point in the line at which the cable failure was observed: either final test or cable attach. This is another aid to the engineer in attempting to isolate the root causes of any cable failures which may have occurred.

4.2.5 Data Collection at Motor Assembly

One way to gage the ease with which a portion of the transducer has been assembled is to measure the time it has taken the operator to complete the task. This is particularly relevant in the case of the motor sub-assembly. After the motor has been wound and placed in the return tube with the magnetic core, it must pass tests for drive voltage and noise level. If these tests are not passed, rework is required. This rework is often more time consuming than the actual assembly process.

On the sheet, the operator records how much time was spent on rework alone, neglecting the initial assembly time which is roughly the same for each sub-assembly. After several methods were tried, the best way to measure rework time is to ask the operator to record only the start and finish times, not the elapsed time. An example of the data collection sheet used at the motor assembly station can be seen in Fig. 4.7.

Originally it was intended that this measurement be tracked using CUSUM SPC techniques. However, the measurements were so erratic, that a proper baseline could not be established and the CUSUM chart was ineffective. Plotting the individual points did prove to be a good graphic method of understanding when the assemblers were having difficulty producing the motor sub-assembly, even though statistically derived control limits were not present.

Model A Cable Assembly Data Sheet

Date	Prod. or Rework	Rework from: Final Test or Cable Att.	If FT, From Probe #:	Problem					
				Open (#	hort (#	EEPROM	Glue	osmeti	Other
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							
	P R	FT CA							

Fig. 4.6 Example of data collection sheet for Model A at cable assembly.

Model A Motor Assembly
Data Collection Sheet

Date	S/N	Time first put moto into test stand	Time Motor Passes Tests	Rework Done/Comments

Fig. 4.7 Example of data collection sheet for Model A at motor assembly.

4.3 CUSUM SPC at the Tank Test

A rash of failures at the tank test led to an investigation by the Corrective Action Team. The following is a description of the problem, poorly defined spec limits led to many false rejections of good transducers, and its solution, to widen the pass/fail spec limits. One long-term aid to the problem is to implement CUSUM control charts at the tank test to be reviewed monthly by the Corrective Action Team. There are 7 different types of Model A transducer, and each type has 7 different critical tank test measurements to it. For this reason, only one measurement (termed VPP) for one type of transducer is discussed here.

4.3.1 Opening the Tank Test Specs

The initial finding from the investigation was that there appeared to be two "types" of failures occurring, "hard" failures, in which the measurements were far from the spec limits, and "soft" failures, in which the measurements were just slightly outside the spec limits. Figure 4.8 shows the VPP measurements for one type of Model A transducer over a period of several months. It is evident that there are a cluster of "hard" failures below 50, but that there are also a number of "soft" failures clustered about the old spec limit of 98.42.

The electrical tests performed on the transducers at tank test are supposed to be a quantifiable approximation to the quality of the image that the transducers will produce. An examination of the "hard" failures shows that these transducers do not function properly and produce very poor, if any, images. An examination of the "soft" failures, however, shows that the image quality on these transducers is indistinguishable from those which are at the target value.

This led to a further investigation to understand how the spec limits were initially derived. It was learned that the spec limits were derived not as specifications for performance, but rather as 3 sigma limits based on a sampling of the first 50 probes built. Clausing [10] is adamant about distinguishing between spec limits, the point beyond which the quality loss to society is less than the cost to rework or reject the part and control limits which identify a process which is deviating from its established baseline. In the case of the tank test, however, the quality loss to society could not be measured because the degradation of image quality proportional to the distance of the tank test measurement from its target value could not be measured.

After much discussion, it was decided that opening up the spec limits on the tank test, and adding a method for monitoring the drifting of the process was a viable solution to the problem. This would eliminate the rejection of good transducers at tank test.

The new spec limits were arrived at by examining data from a large number of recently built probes. To determine the new spec limits, the first step was to examine the data without the "hard" failures. These points were clearly outliers to the data which should not influence the calculations. Figure 4.9 shows the data from Fig. 4.8 with the outliers removed; it was this data which became the baseline for all future calculations.

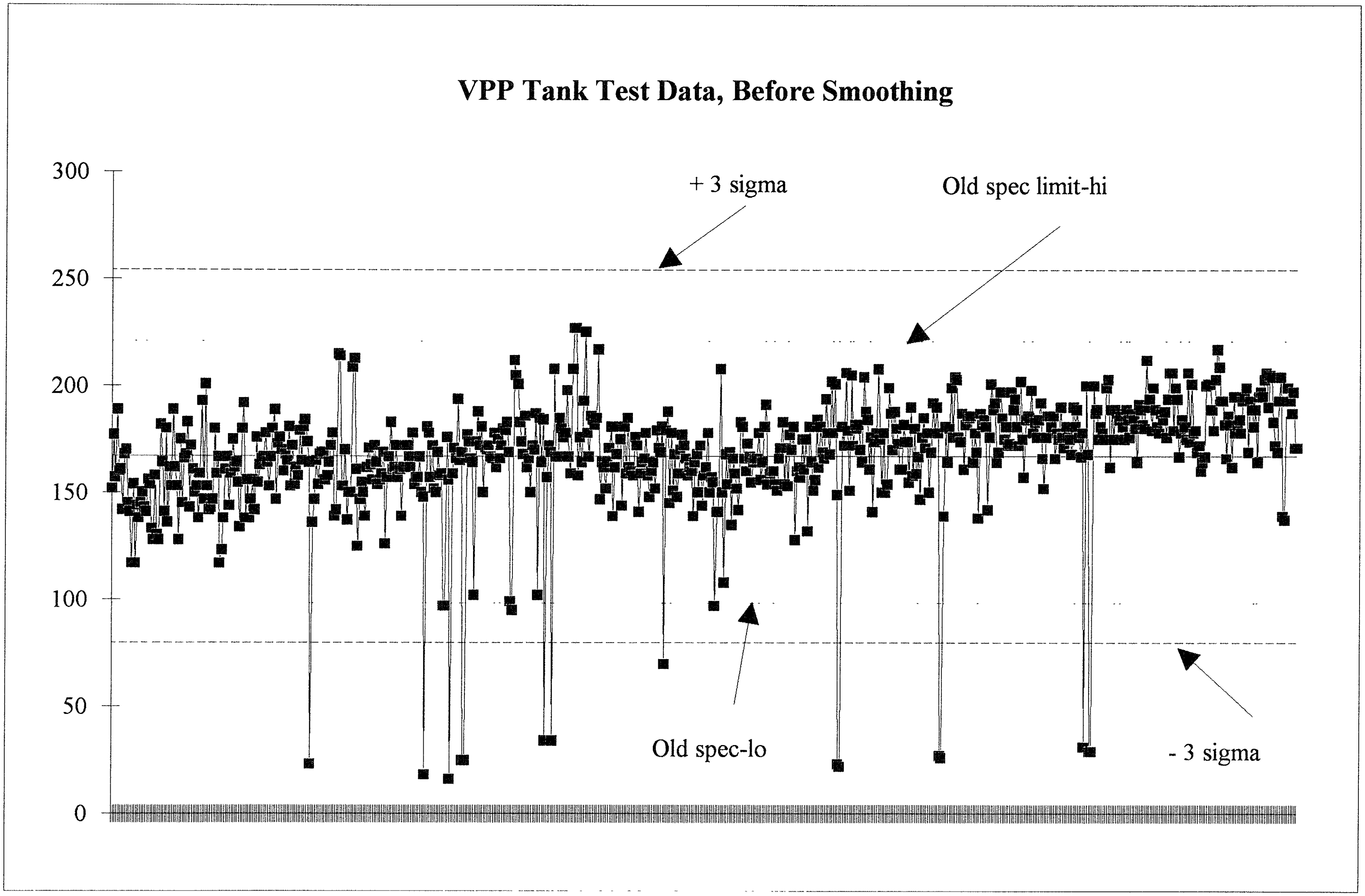


Fig. 4.8 VPP tank test data which became basis for new spec limits, before smoothing.

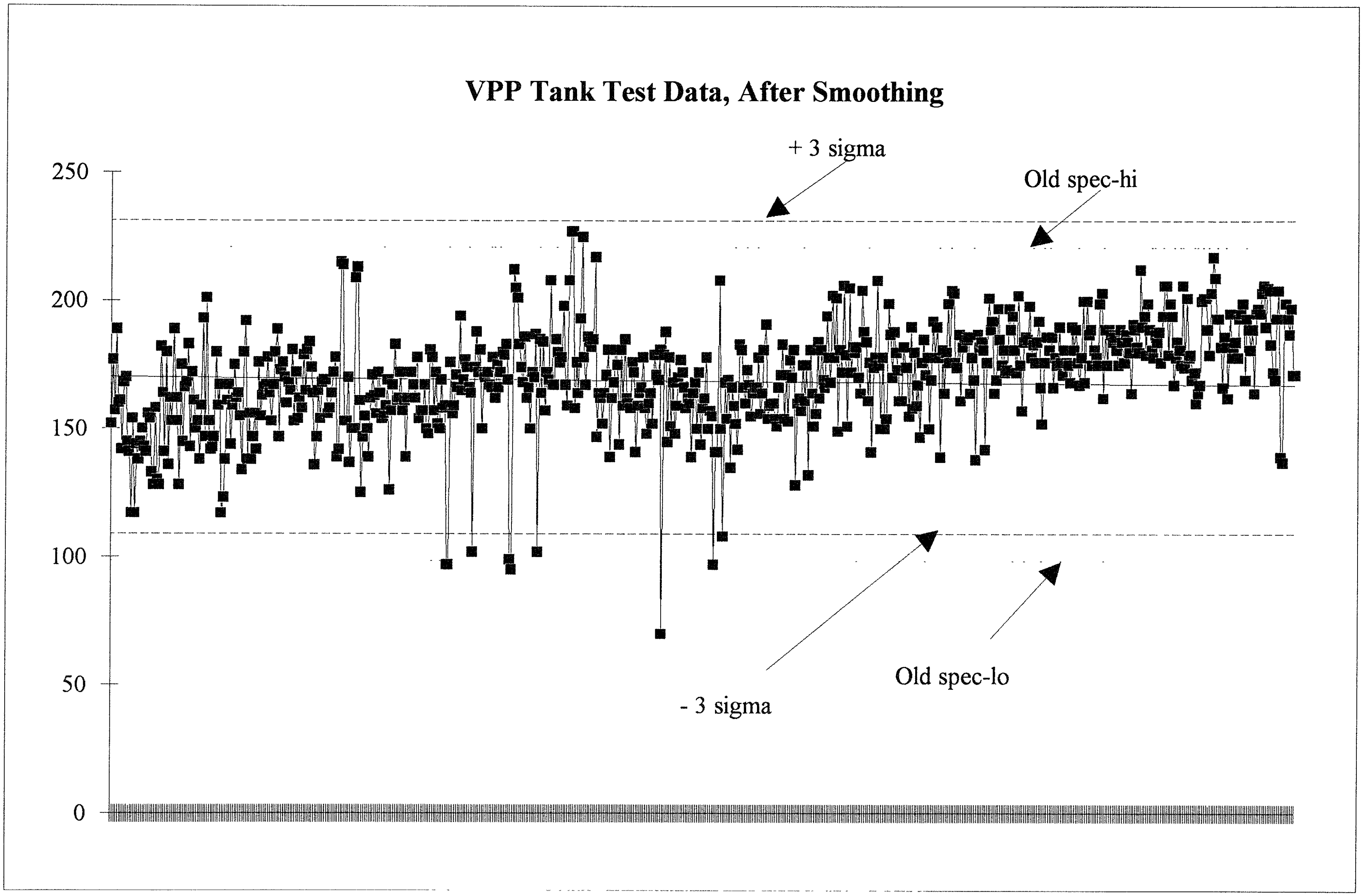


Fig. 4.9 VPP tank test data which became basis for new spec limits, after smoothing.

Next, the mean and standard deviation were computed on the smoothed data. Finally, the new target value for the test was taken to be the mean of the smoothed data, and the spec limits were taken to be either the old 3 sigma limits or the new 3 sigma limits, whichever was further from the mean. Clinical tests were performed on probes meeting these new specs, and no difference in image quality could be detected.

4.3.2 Implementing CUSUM SPC

Once the specs had been opened, the Corrective Action Team required a means for monitoring the process for drifts from the target. Statistical process control is an effective means for monitoring a process such as the tank test, which has a continuous variable quality metric.

Cumulative sum (CUSUM) charts were selected as the means of process control for several reasons [28, 31]: The CUSUM chart is effective in detecting small shifts in the process, the chart is effective for dealing with low-volume processes in which it is desirable to plot individual measurements, rather than a rational subgroup of samples, and the CUSUM technique includes information about the history of the process, rather than just the last plotted data point. A tabular CUSUM chart was selected because it is easier to implement on a computer than the v-mask technique. Because there are 49 charts to monitor (7 types with 7 different measurements), it is necessary to process the data by computer.

The design of the CUSUM chart was conservative. Following the CUSUM control chart parameter selection table in Montgomery [31 p. 289], the values of A, d, and L were selected to detect a process shift of 2 standard deviations and have an average run length of 500 when the process is under control. This was done to ensure that the fewest false alarms would occur. There is generally a trade-off in designing a control chart between speed of detection of an out-of-control point and frequency of false alarms. Because the Corrective Action Team will be looking at the charts on a monthly basis, the trade-off of slow response time for infrequent false alarms is an economical one to make.

Finally, there is the question of outlier points, such as those seen on Fig. 4.8 and 4.10. Fig. 4.10 shows a sample of VPP data points to be plotted on the CUSUM chart. Techniques for designing robust control charts, charts insensitive to the effects of outlier points, have been developed [36, 37, 38]. However, in the case of the tank test, the outlying points are obvious and irrelevant to the type of information that the CUSUM chart seeks to control. It is well known that these outlier points were caused not by random variation, but by transducers which are faulty for other reasons. Rather than developing robust control charts, it was decided to "smooth" the data by removing the obvious outliers prior to charting. For example, Fig. 4.11 shows the smoothed VPP data which will was used in the CUSUM chart.

The CUSUM chart for the VPP data is shown in Fig. 4.12. Control limits have been established and are shown and are representedby the horizontal lines across the graph. The CUSUM chart is quick to identify an upward shift in the data, as evidenced by the graph of the data in Fig. 4.11. It is clear that corrective action to the process will be required. The large build-up on the high side of the chart indicates that the process is still drifting to the high side of the spec. The Corrective Action Team should analyze these figures, develop a plan of action, and follow through on returning the process to a state of control.

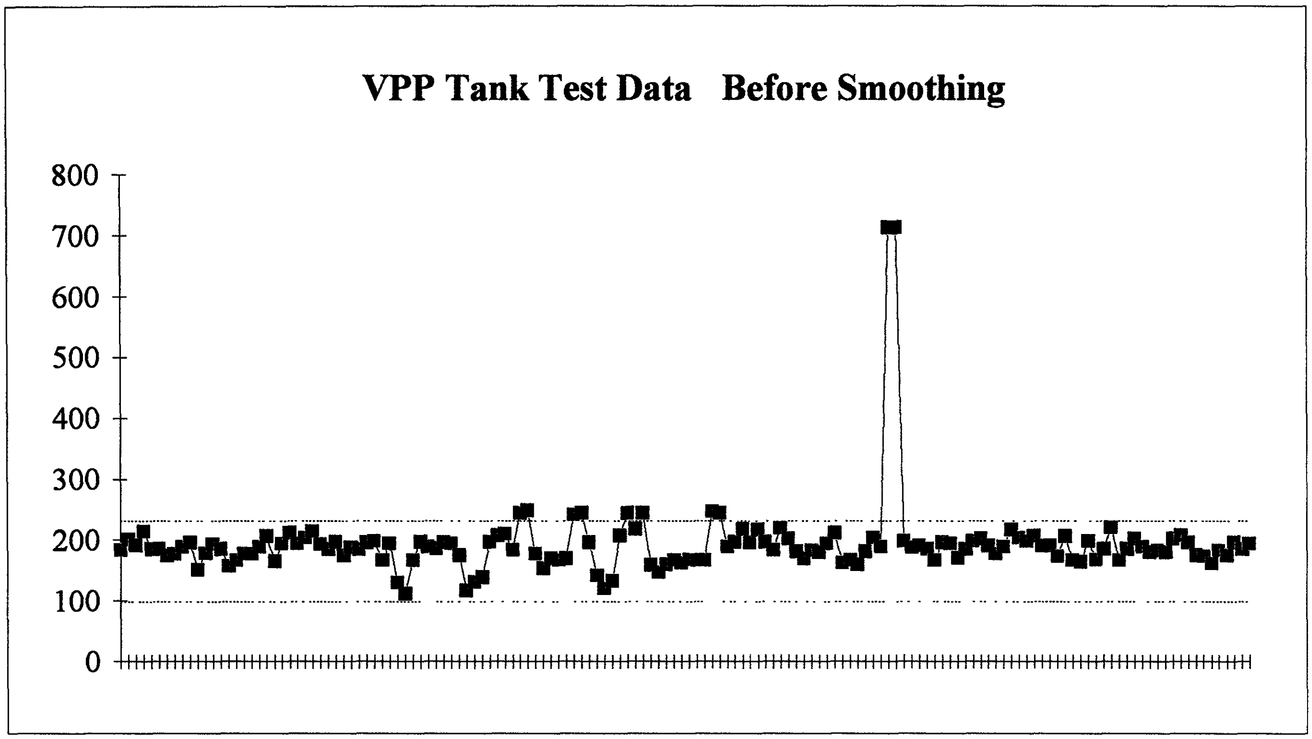


Fig. 4.10 VPP tank test data for a type of Model A transducer, before smoothing

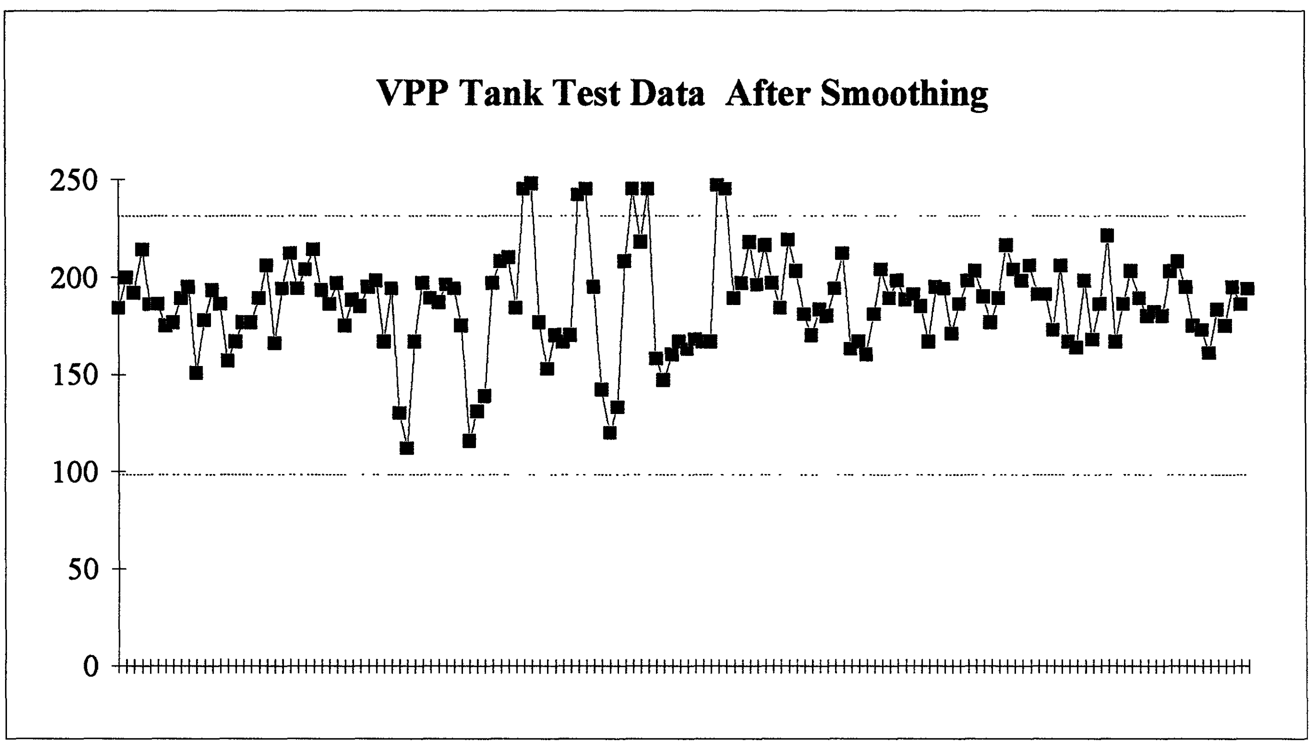


Fig. 4.11 VPP tank test data for a type of Model A transducer, before smoothing

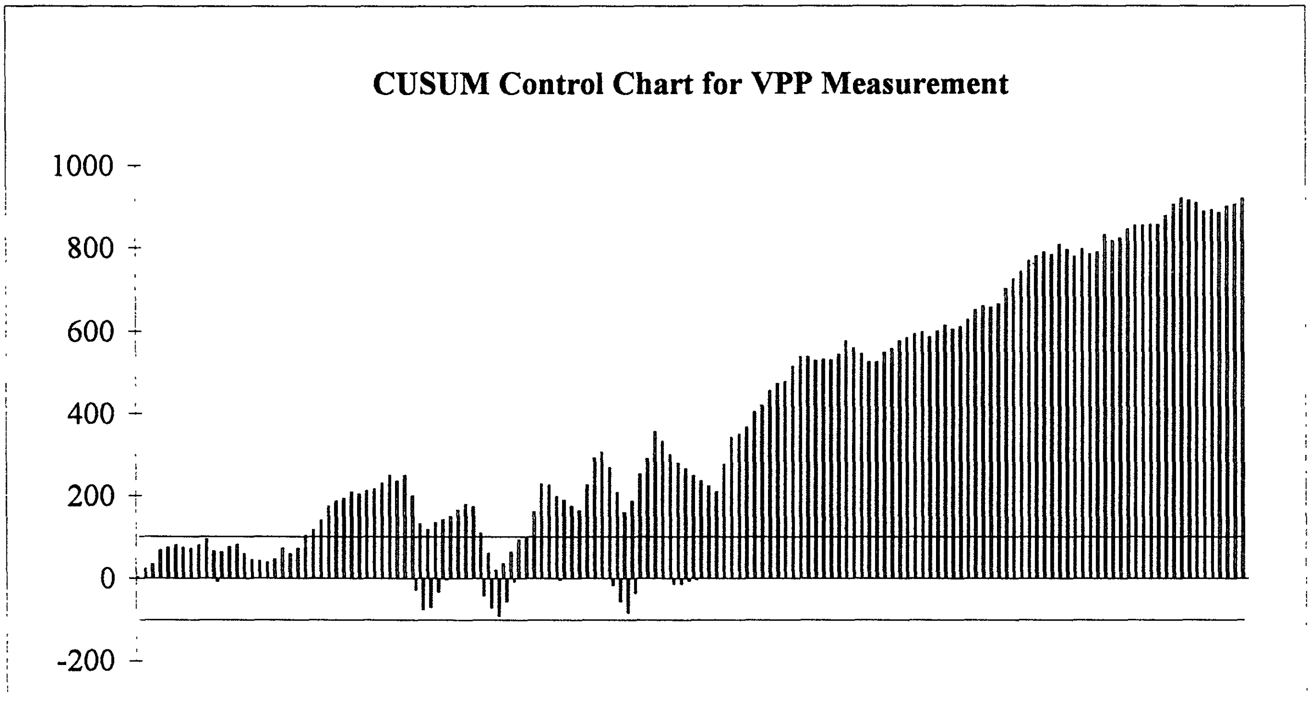


Fig. 4.12 CUSUM control chart for VPP data seen in Fig. 4.11.

V. Results of the Process Control Scheme

This chapter presents several different means for evaluating the results of the efforts to both bring the process into control and to implement a means of data-driven process control on the mechanical transducer production line. Next an example is presented which shows both how some of the data collection sheets were derived and how effective they can be in identifying problems and helping engineers determine the root cause of these problems.

5.1 Performance Evaluation

Several measures of the performance of the mechanical transducer production line are presented in Figures 5.1 - 5.4. Figure 5.1 shows the final test yield for each week of a 5 month period, given in 30-day moving window increments. Prior to the data collection system, production output efficiency then grew rapidly from a modest initial level and held at peak levels of 95% or better. January saw the rotation of the operators to new jobs within the transducer area. Correspondingly, the output efficiency fell dramatically, bottoming out at 75%. Corrective action to the process and increased familiarity of the operators with their new jobs has steadily brought the efficiency back up over 90%.

Looking at the old method of first pass yield in Fig 5.3 over the same time period shows that, even in the months in which final test yield dropped to 75%, first pass yield was still above 85%. This discrepancy is due to the fact that the final test yield metric accounts for transducers which fail final test more than once. This indicates that many of the problems on the mechanical transducer line come from probes which fail several times before passing. Recommendations are made in Chapter 6 about how to address this problem in the future.

Figure 5.2 shows the first pass yield for the final assembly (cable attach) station, based on the data collection sheets of Fig. 4.3. Since the implementation of the data collection scheme, the yields at this station have been extremely high, all over 95%. The final three weeks of 30-day moving window calculations had no failures, and, therefore, 100% yield. Prior to implementation, yields had been significantly lower, estimated at 85%. Some changes to the process, including a new gluing syringe and new rubber for the locking ring torque wrench, helped bring this process to its currently high efficiency.

The pareto chart in Fig. 5.4 demonstrates how the weekly reports can be pooled together to yield a big-picture view of the failures that have plagued the production line. This chart documents the identified failures over a six month period just prior to and at the beginning of the implementation of the data collection scheme.

Of the top 5 problems, representing over 80% of the failures, 4 have been directly addressed by the corrective action team: tank failures with the relaxation of the spec limits (Chapter 4); "noisy" with the solution to the shaft/spring problem (Chapter 3); "hitting cap" with the solution to the hitting cap problem (Chapter 3); and "bad cable" with the solution documented in Section 5.2 below. It is for this reason that the data-driven process control

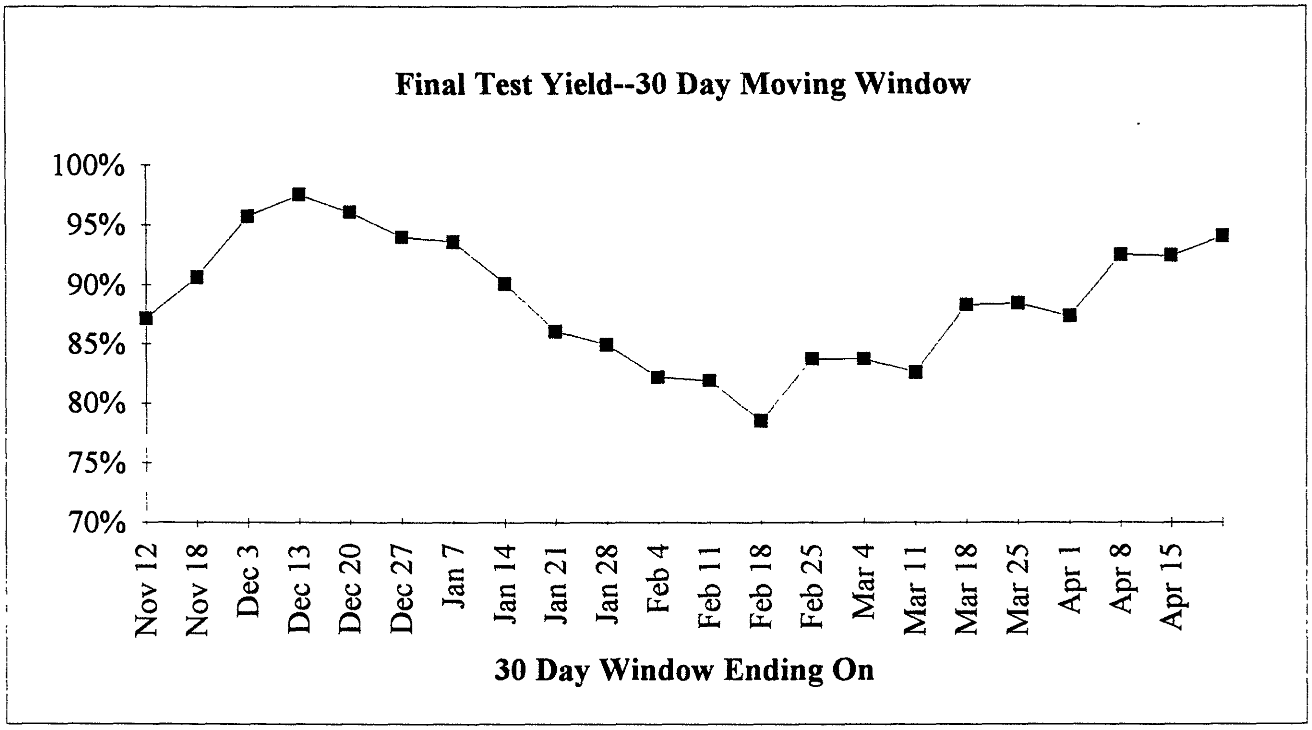


Fig. 5.1 Graph of yields based on 30-day moving average from data from final test sheets.

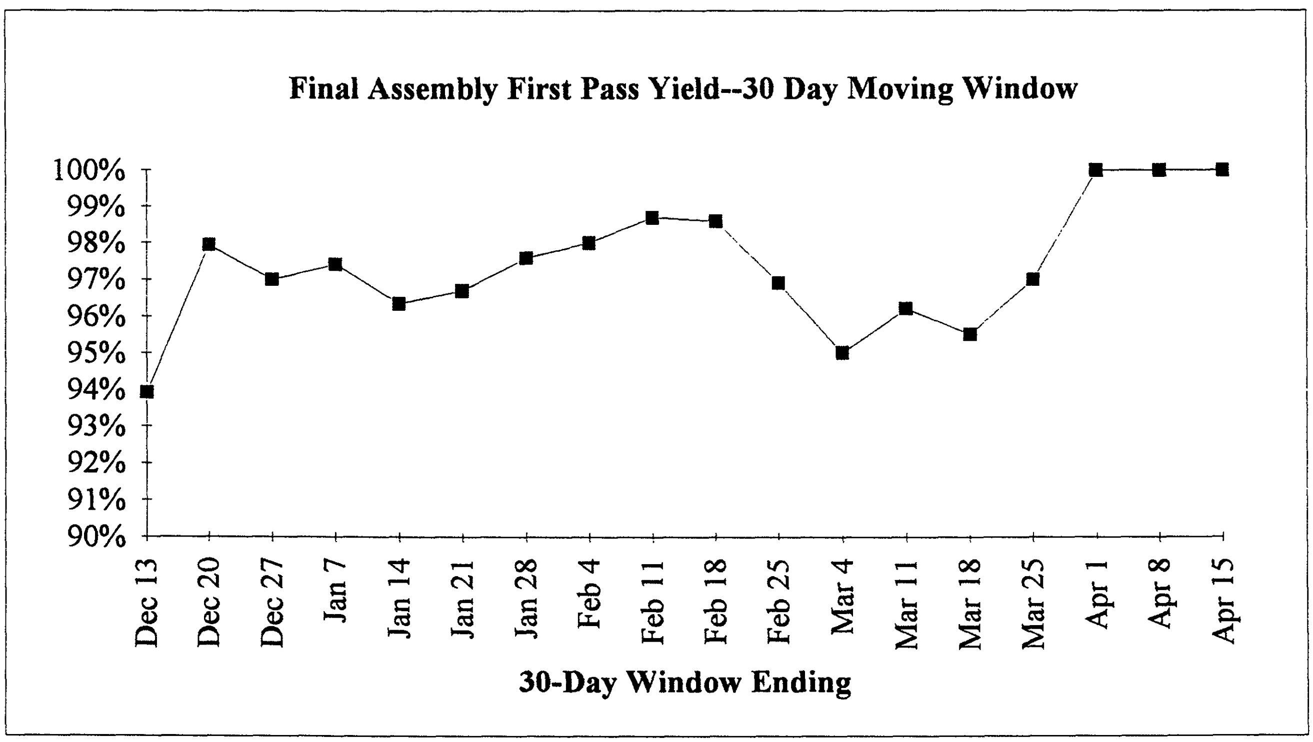


Fig. 5.2 Graph of yields based on 30-day moving average from data from final assembly sheets.

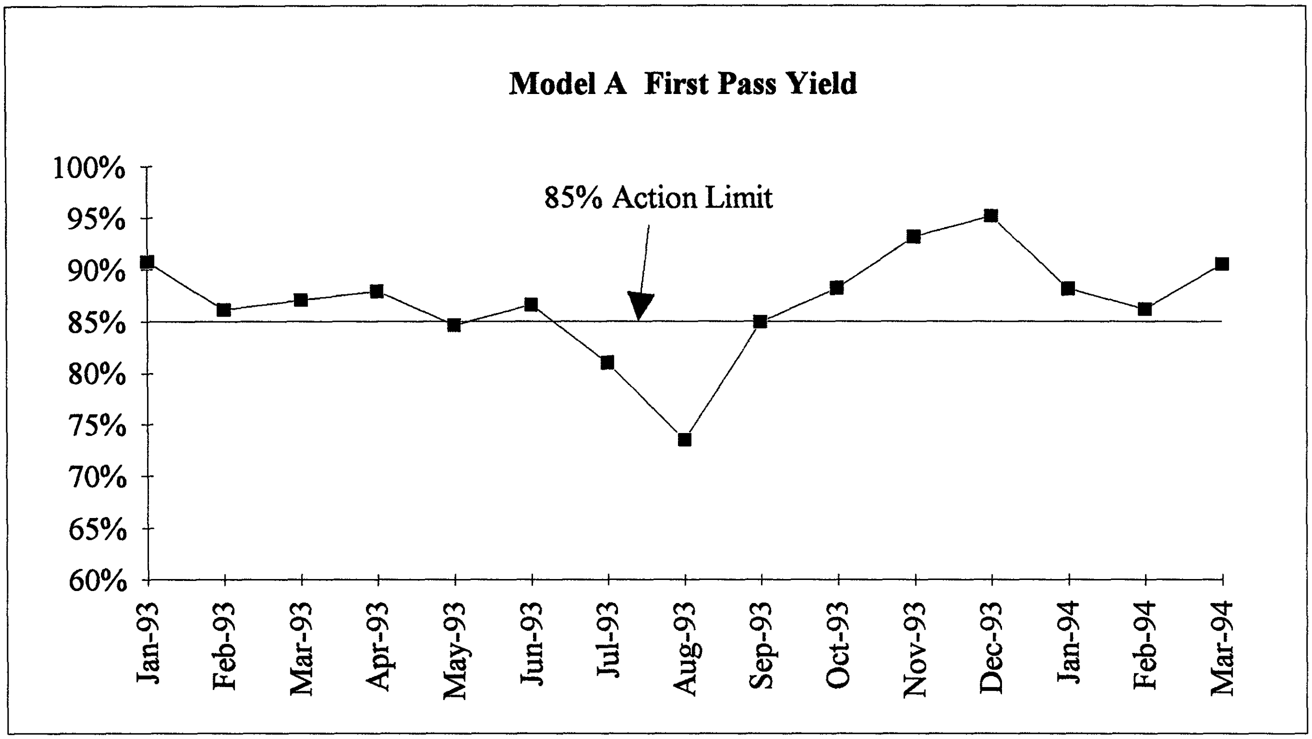


Fig. 5.3 Graph of Model A first pass yield, as measured by corrective action team.

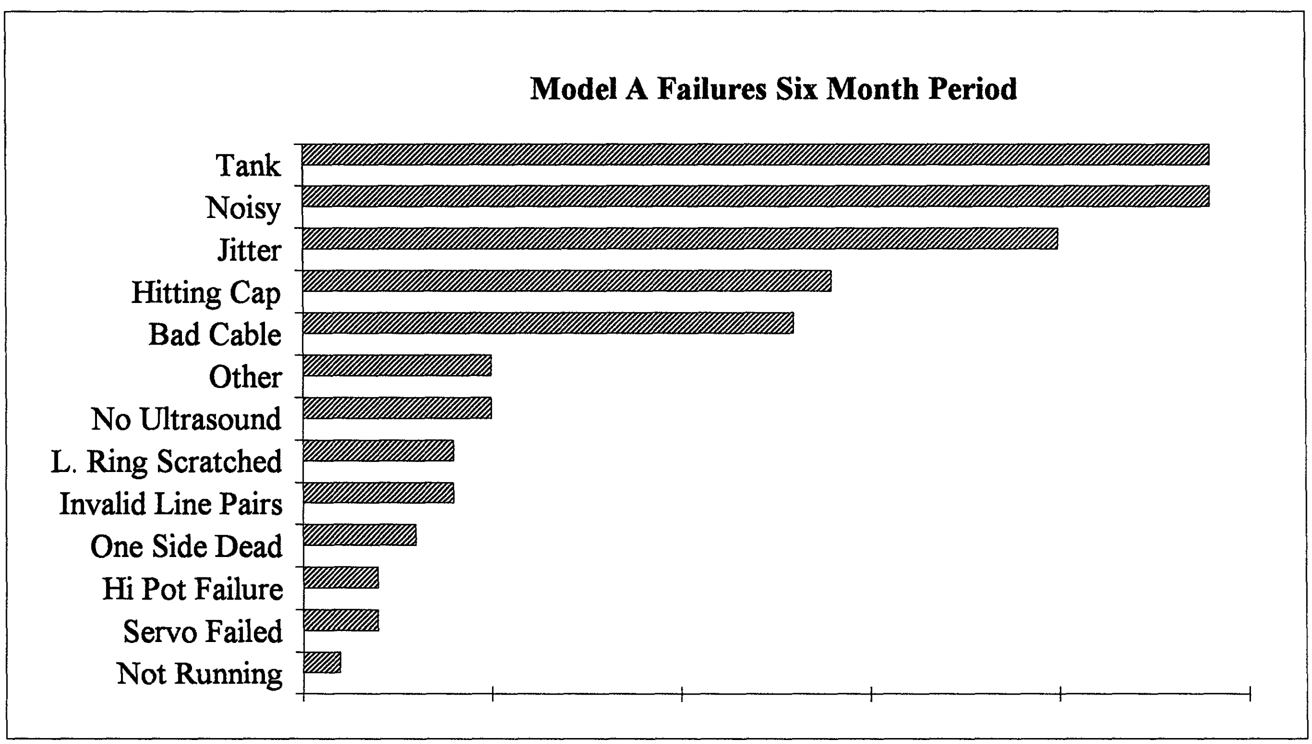


Fig. 5.4 Pareto chart of Model A failure modes over a six month period.

scheme implemented on the mechanical production line can be deemed at least moderately successful in addressing problems on the line and improving the process efficiency and output.

5.2 Example of the Use of the Control Scheme

The example contained in this chapter is intended to show both the derivation of some of the data collection sheets and how the data collection scheme can be used to effectively identify and troubleshoot problems on the line.

The monthly reports used by the corrective action team prior to the implementation of the data collection scheme contained a record of "bad cable" problems which had been plaguing the line for several months. Because the number of these incidents exceeded the arbitrarily defined action limit, an engineering investigation was launched.

The crude data collection sheets shown in Figures 5.5 and 5.6 were developed and deployed to the operators to help find the root cause of the problem. The sheet in Fig. 5.5 indicated that the majority of failures were identified at cable attach, but were a result of work done at the cable assembly station.

Also in Fig. 5.5 is a breakdown of the type of failures that had been occurring. The majority of failures were open circuits occurring at one of the outside prongs of the male connector end of the cable. Further investigation revealed that the operator at the cable assembly station, new to the job, had been stripping too much insulation off the wires, leaving brittle copper wire exposed. When the cables were handed off to cable attach, they operated properly, but the twisting of the cable during cable attach made some of these brittle wires break and caused the cables fail.

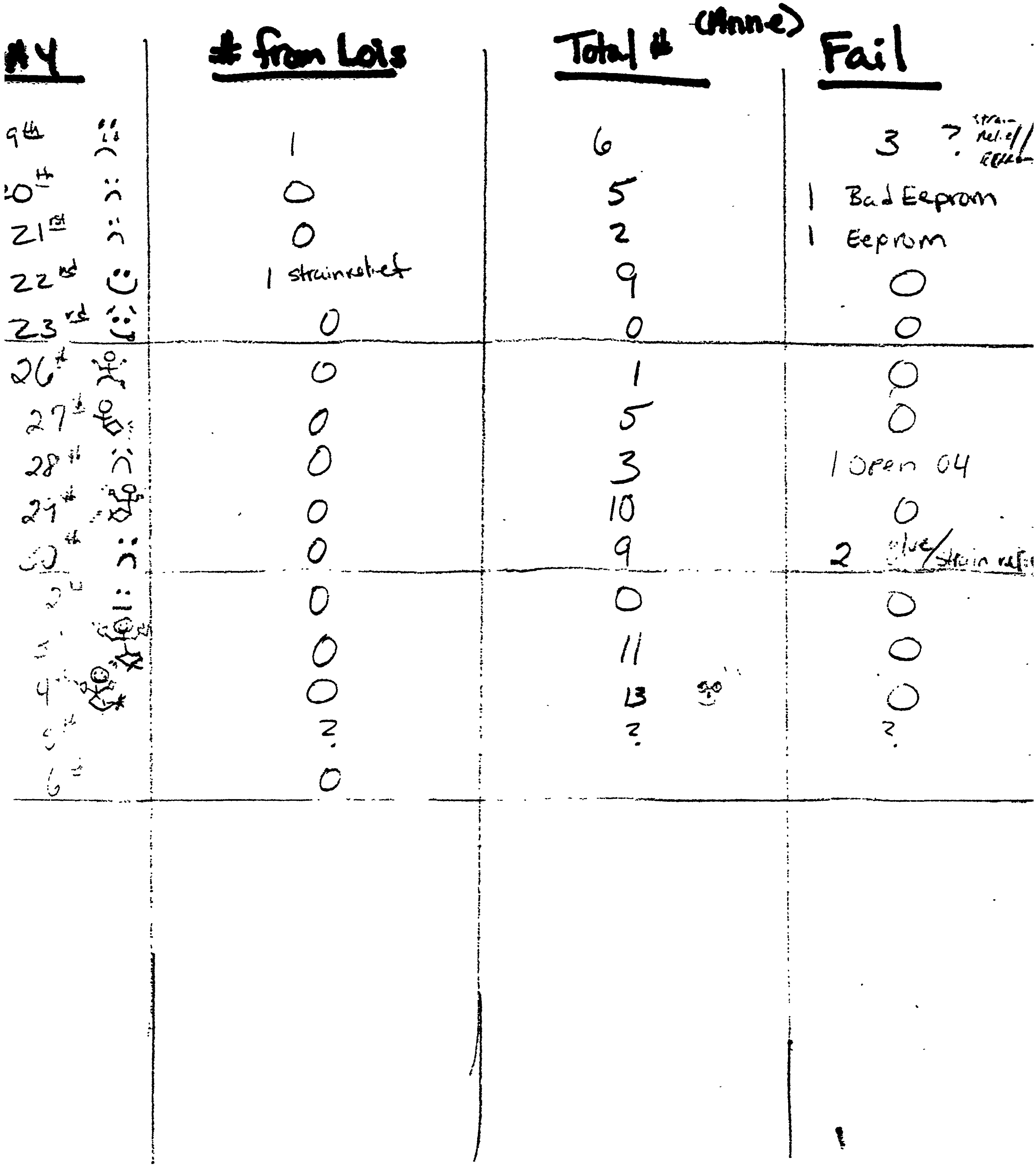
The corrective action initiated was to create a jig indicating to the operator at cable assembly how far back to strip the insulation off the wire, so as to still be able to solder the wire to the connector yet not be so fragile that failures would occur further down the line. This action was effective in almost immediately ending the string of cable failures.

Although at the time these crude data collection sheets were put in place to help fix a specific problem, it is easy to see how the best features of these sheets were taken to create the much more effective, polished ones in Fig. 4.2 and 4.6. Similarly, the method of rapid identification of a problem, and top-down approach to pinpointing the root cause of the problem is one that has been used several times since the initiation of the data-driven process control scheme.

Cable Assembly Failures

Date	Rework (from Anne)	Production (from Lois)
7/20	STR. Relief	OPEN 04
	Str. Relief	OPEN 00
	Str. Relief	OPEN 00 (2x), SHORT 05 (1), BAD GLU
	BAD EPROM	
7/22	EPROM	EPROM
	EPROM	OPEN 00
	OPEN 04, 07, 00	OPEN 00
	OPEN 06	
7/26	STR Relief	—
	Str. Relief	
	OPEN 05	
7/29	BAD GLUE (Str. Relief)	—
	BAD Glue (Str. Relief)	
7/30	OPEN 04	
	GLUE	
8/11	OPEN 04	

Fig. 5.5 Early data collection sheet at cable assembly, showing the types of failures occurring.



#Y	# from Lois	Total # (Anne)	Fail
9th	1	6	3 ? strain relief / Eeprom
20th	0	5	1 Bad Eeprom
21st	0	2	1 Eeprom
22nd	1 strainrelief	9	0
23rd	0	0	0
26th	0	1	0
27th	0	5	0
28th	0	3	1 Open 04
29th	0	10	0
30th	0	9	2 glue/strain relief
2nd	0	0	0
3rd	0	11	0
4th	0	13	0
5th	?	?	?
6th	0		

Fig. 5.6 Early data collection sheet at final assembly, showing the origin of the cable failures.

VI. Conclusions and Recommendations

At the conclusion of the research done for this thesis, there were many insights gained into both the implementation of data-driven process control techniques and into the productivity of the mechanical transducer production line at Company X. There was also much work left incomplete due to time restrictions. These insights of incomplete work are presented in this chapter in the form of conclusions and recommendations for future work. In many cases, the two are intertwined, as recommendations for continuing process improvement and process control have come about due to insights gained from working on the production line.

1. <u>The majority of problems on the production line are due to two causes</u>:

- faulty raw materials or OEM parts from suppliers
- inexperience when assemblers switch assignments

Faulty raw materials or OEM parts from suppliers is a problem which is very common, and very devastating to a low-volume production line. Although Company X tries to maintain minimal inventory, it is not economical for its suppliers to build parts in such small volumes as Company X would require to maintain a "just-in-time" queuing system. Therefore, even if Company X receives shipments of very small quantities, often the supplier has built a large quantity in a single batch run, and is holding the inventory in his warehouse, instead of being on Company X's production line.

This can be devastating to a low-volume production line for the following reason: when a parts defect has been identified in the parts currently being used for production, the problem usually has been repeated on all the parts in that batch remaining in the supplier's inventory. Consequently, it is very expensive and time consuming for a supplier to rework all the parts in the batch, which he must do since it would be even more expensive to produce another batch. This expense is generally not incurred in a continuous flow manufacturing process, in which the process can be changed as products are being made.

A particular example of faulty OEM parts described in Chapter 3 was the case of the hitting cap problem, in which the caps that the supplier had built deviated in inside height from ones that had previously been built.

The second identified cause, inexperience when assemblers switch assignments, has come about due to the commitment of the line supervisor to rotating the line personnel through all of the stations for assembling both Model A and Model B transducers. There are many benefits to such a system, but one drawback is the process may experience difficulties for a time while the assemblers are learning their new assignments.

The standard process procedures have been written to convey to any new assembler the exact instructions (including subtle "tricks" that assemblers have learned over time) for how to do a particular job. Nevertheless, there is usually a learning period that any assembler has to go through before he is fully comfortable with producing the required sub-assembly. It is sometimes difficult to convey, either in written procedures or by word of mouth from operator to operator, every exact detail of the job. Examples of this type of problem causing problems on the line are the audible noise problem described in Chapter 3 and the faulty cable problem described in Chapter 5.

The exercise of implementing a means of data-driven process control described in the previous chapters has demonstrated that the process is capable of running at a very high level of quality. Very high yields can be achieved without the influence of these two primary types of "assignable cause". Although the assemblers are very competent and steady in their work (neglecting the influence of the above factors), it would be very difficult with a hand-assembly process to remove each and every "random cause", usually human error.

Rather, the data-driven process control scheme described in the previous chapters provides a means for rapidly identifying the problem areas of the process and for easily analyzing the root cause of these problems. To this end, the following two recommendations are made for reducing the effect of these two assignable causes.

2. <u>Implement a means for tracking the influx of new parts.</u>

Due to the low production volumes, cost efficiencies dictate that batch processes have to be used both by suppliers and by the mechanical transducer production line. A way to deal with this is to install a system within the inventory queues on the production line to indicate the date and on what transducer the first unit from each batch was used. This will make identifying the root cause of production problems much easier, as engineers will be able to know from the data-collection system on which probe the problem first occurred, and from this batch inventory system which parts were taken from a new batch.

This idea has been discussed among the members of the corrective action team. It was decided to postpone the idea for an indefinite amount of time, until the operators become more comfortable with data collection. It was felt that some of the operators are already burdened with paperwork, and to add more would cause discontent.

3. <u>Provide for better training and transfer of knowledge to minimize the effect of switching jobs.</u>

Although the job rotation program was initiated in part to give the operators a more global feel for the mechanical transducer assembly process, the operators still have only a local understanding of the particular job they are doing. More should be done to give the operators a more overall view of how the product works and how each job they do influences the quality of the product downstream. Specifically, it is recommended that the following be done:

- give the operators a demonstration by a sonographer of the product at work
- describe to the operators how the product works from a technical standpoint

Most of the operators have never seen the transducer creating an image of a heart beating, and therefore have little feel for how the transducer is supposed to function after it is fully built. This also leads to a lack of understanding as to why the transducer must pass certain tests before it can be shipped. Most of the operators do not understand how the transducer creates an image or how the parts within the transducer operate. This means that they have little idea as to how the sub-assembly that they are producing fits in with all the other parts of the transducer.

This idea has been proposed to the corrective action team, and it was acknowledged to be a valuable part of operator training. However, the sonographers who demonstrate the product and the marketing personnel who can give the best technical product description for non-engineers have not been available to begin the training. This proposal should be followed up, however, as it will be valuable for the health of the production process.

4. Complete the stages necessary to implement SPC at the motor assembly station

The motor assembly station is an ideal part of the process in which a statistical process control scheme similar to the one on the tank test could be implemented. Continuous variable measurements–drive voltage and noise level–are taken and recorded for every motor built. However, the test equipment used to make these measurements could be easier to use. An attempt was made to replace the test equipment with a new design, but that design has not yet been proven out.

This was the wrong course of action, however. Efforts to improve the motor building process would have been more fruitful than efforts to change the test device. As Demming has advocated, over reliance on build-and-test should be discouraged. It is only after the process has become robust and the variation of the process minimized, should efforts be steered towards process control techniques and measurements. A greater impact to the overall mechanical transducer production process could be achieved if this course of action had been followed.

The following course of action is recommended:

- examine the motor building process and change as necessary to cut down the variability of the output and the time required to rework motors
- replace the motor test stand with a measuring device which is easier to use
- use CUSUM charts similar to those used for the tank test to control the level and variance of the motor building process

5. Create a table of common fixes to common failures.

One observation that has been made throughout the course of this research is that if a probe fails once, it is likely that it will fail again a second or third time. Often this happens because the assembler does not understand the root cause as to why the probe has failed. Many times this is because the assembler does not understand the test that is being performed, and what it is supposed to test for. In this case, the assembler makes a best guess as to the root cause of the problem, usually based on prior experience, and changes a part or sub-assembly accordingly. Sometimes this works, but often times it does not, and the result is a probe that is built and rebuilt several times before it can be shipped.

Perhaps this problem will be addressed once suggestion 3, above, is implemented, giving the operators a better understanding of the process and of the tests that are being performed. However, a direct approach to this problem should also be taken. It is recommended that a table be created by production engineers which lists all the failure modes that can be experienced by the transducer at final test, and the series of steps the operator should follow to diagnose and fix these problems. This will not eliminate the need for engineering support of the line, which is responsible for diagnosing and eliminating complicated problems, but may reduce the number of transducers with common problems that fail two and three times before passing.

Some efforts have been made to this end. A listing of the error code messages for the imaging test and for the tank test and a description of what the codes mean have been requested from R&D. Once these are obtained, production engineers can easily translate these codes into a "common fixes" table. It is expected that this measure will help reduce production cycle times and increase the health of the process.

Appendix A

This Appendix contains the raw data collected in performing the toroid winding machine robustness optimization experiments described in Section 3.3.

Expt. #	Initial Inductance (mH)				Inductance (mH) Hi/Lo							
	Core speed fromLo Side		Core Speed from Hi Side		Core Speed set from Lo Side				Core Speed set from Hi Side			
	1st	2nd	3rd	4th	1st		2nd		3rd		4th	
1	205.5	199.7	176.6	176.3	209.6	170.0	206.3	170.6	187.3	152.2	179.4	164.8
2	XXX	165.4	173.3	166.0	XXX	XXX	188.1	152.8	178.0	147.6	172.3	156.6
3	176.0	179.0	163.7	163.4	183.2	163.0	184.4	155.7	173.0	143.0	172.1	159.6
4	193.3	187.7	161.8	180.3	197.6	166.8	191.0	157.4	183.8	161.8	183.7	155.7
5	179.4	184.7	162.6	XXX	181.6	161.2	186.5	155.3	173.8	151.8	XXX	XXX
6	200.4	201.1	180.7	177.7	200.4	171.4	201.9	167.2	182.8	164.7	182.9	160.5
7	184.3	170.5	155.5	144.4	189.4	161.5	175.4	150.9	166.0	146.3	166.4	144.4
8	195.6	184.7	171.7	177.5	198.3	162.1	189.9	157.9	175.3	148.3	182.4	162.0
9	177.8	177.8	155.5	158.6	186.0	143.9	185.5	149.2	169.7	145.6	167.9	148.4
10	189.2	193.3	166.8	163.0	194.5	171.0	195.6	167.9	172.0	155.2	170.7	153.4
11	180.5	170.7	154.2	XXX	190.4	162.4	180.9	153.9	172.7	140.9	XXX	XXX
12	202.6	192.4	171.6	181.1	203.5	161.2	198.2	155.5	176.9	154.7	189.0	165.5
13	200.3	209.1	181.5	183.4	207.0	170.7	197.0	186.6	185.0	162.3	188.4	164.4
14	185.0	185.7	XXX	169.6	189.7	162.2	187.0	158.9	XXX	XXX	172.7	162.5
15	164.9	170.4	162.6	158.4	172.7	148.8	174.3	157.8	171.9	155.8	170.6	143.2
16	176.3	178.1	164.4	164.3	179.1	166.1	181.3	164.3	173.4	153.7	174.2	151.9
17	192.2	184.1	185.9	176.1	197.4	167.2	199.7	151.5	187.7	168.3	181.6	161.3
18	168.7	177.1	163.4	154.4	176.3	154.2	181.4	153.3	174.2	155.5	168.9	144.0

Fig. A-1: Raw data for first round (L_18) of toroid winder robustness optimization. XXX indicates that toroid was damaged during cutting and could not be measured.

Expt. #	Initial Inductance (mH)			Inductance (mH) Hi/Lo					
	Lo Side		Hi Side	Lo Side				Hi Side	
	1st	2nd	3rd	1st		2nd		3rd	
1	192.5	192.1	166.5	163.2	194.7	162.4	195.0	156.2	177.7
2	180.0	187.3	162.5	158.4	184.7	161.3	189.6	158.2	172.4
3	166.6	172.6	154.2	153.9	176.6	155.3	179.2	143.8	172.4
4	186.6	181.6	153.9	165.5	191.1	148.2	189.2	144.5	163.6
5	189.4	183.5	158.2	163.0	184.0	162.6	189.4	146.6	168.0
6	166.3	176.5	160.0	154.5	173.3	162.3	183.1	149.0	169.1
7	183.1	187.7	169.0	158.0	191.0	156.4	195.1	152.1	193.0
8	180.2	170.1	160.8	163.3	184.9	154.0	176.5	155.2	166.8
9	181.9	163.0	161.7	165.7	187.1	155.5	180.4	141.0	168.5

Fig. A-2: Raw data fro second round (L_9) of toroid winder robustness optimization experiments.

References

[1] AFS Green Sand Molding Committee, "SPC for Small to Medium Foundry's Sand System: Part 1", *Modern Casting*, Vol. 79, No. 9, pp. 53-55, September 1989.

[2] AFS Green Sand Molding Committee, "SPC for Small to Medium Foundry's Sand System: Part 2", *Modern Casting*, Vol. 79, No. 10, pp. 28-30, October 1989.

[3] AFS Green Sand Molding Committee, "SPC for Small to Medium Foundry's Sand System: Part 3", *Modern Casting*, Vol. 79, No. 11, pp. 42-44, November 1989.

[4] Banks, Lawrence W., "An Ultrasound Imaging System", *Hewlett-Packard Journal*, pp. 6-11, October 1983.

[5] Benjamin, Marti, and J. Shaw, "Harnessing the Power of the Pareto Principle", *Quality Progress*, pp. 103-107, September 1993.

[6] Box, George, and T. Kramer, "Statistical Process Control and Automatic Process Control–A Discussion", *Report Series in Quality and Productivity*, Report No. 41, Center for Quality and Productivity Improvement, University of Wisconsin, Madison, WI, January 1990.

[7] Box, George, and J. Ramirez, "Sequential Methods in Statistical Process Monitoring", *Report Series in Quality and Productivity*, Report No. 65, Center for Quality and Productivity Improvement, University of Wisconsin, Madison, WI, May 1991.

[8] Box, George, and J. Ramirez, "Sequential Methods in Statistical Process Monitoring Chapter 3: Design of CUSUM Charts", *Report Series in Quality and Productivity*, Report No. 66, Center for Quality and Productivity Improvement, University of Wisconsin, Madison, WI, May 1991.

[9] Burr, John T., "Tools of Quality. Part I: Going With the Flow(chart)", *Quality Progress*, Vol. 23, No. 7, pp. 59-62, July 1990.

[10] Clausing, Don P., *Total Quality Development*, working draft of a book for imminent publication, 1993.

[11] Clausing, Don P., "Taguchi Methods Integrated into the Improved Total Development", *Proceedings of IEEE International Conference on Communications*, pp. 0826-0832, Philadelphia, June 1988.

[12] Cullen, Chad C., and D. Bothe, "SPC for Short Production Runs", *IEEE Proceedings of the National Aerospace and Electronics Conference*, Vol. 4 (of 4), pp. 1960-1963, 1989.

[13] Deming, W. E., *Quality, Productivity, and Competitive Position*, Massachusetts Institute of Technology, Center for Advanced Engineering Study, Cambridge, MA, 1982.

[14] Duncan, A.J., *Quality Control and Industrial Statistics*, 4th Edition, Richard D. Irwin, Inc., Homewood, Ill, 1974.

[15] Farnum, Nicholas R., *Modern Statistical Quality Control and Improvement*, Duxbury Press, Belmont, CA

[16] Gan, F.F., "An Optimal Design of CUSUM QUality Control Charts", *Journal of Quality Technology*, Vol. 23, No. 4, pp. 279-286, October 1991.

[17] Guo, Ruey-Shan, and E. Sachs, "Modeling, Optimization, and Control of Spacial Uniformity in Manufacturing Processes", Submitted to *IEEE Transactions on Semiconductor Manufacturing*, September 1991.

[18] Hackl, Peter, and J. Ledolter, "A Control Chart Based on Ranks", *Journal of Quality Technology*, Vol. 23, No. 2, pp. 117-124, April 1991.

[19] Hahn, Gerald J., "Improve Quality with Data-Driven Analytics", *Quality Progress*, pp. 83-86, October 1993.

[20] Hahn, Gerald J., "Experimental Design in the Complex World", *Technometrics*, Vol. 26, No. 1, pp. 19-31, February 1984.

[21] Hawkins, Douglas M., "Robustification of Cumulative Sum Charts by Winsorization", *Journal of Quality Technology*, Vol. 25, No. 4, pp. 248-261, October 1993.

[22] Holmes, Donald, "SPC Techniques for Low-Volume Batch Processes", *Ceramic Bulletin*, Vol. 69, No. 5, pp. 818-821, 1990.

[23] Iglewicz, Boris, and D. Hoaglin, "Use of Boxplots for Process Evaluation", *Journal of Quality Technology*, Vol. 19, No. 4, pp. 180-190, October 1987.

[24] Karrer, H. Edward, and A.M. Dickey, "Ultrasound Imaging: An Overview", *Hewlett-Packard Journal*, pp. 3-6, October 1983.

[25] Kenett, Ron S., "Two Methods for Comparing Pareto Charts", *Journal of Quality Technology*, Vol. 23, No. 1, pp. 27-31, January 1991.

[26] Koons, George F., and J. Luner, "SPC in Low-Volume Manufacturing: A Case Study", *Journal of Quality Technology*, Vol. 23, No. 4, pp. 287-295, October 1991.

[27] Kramer, Tim, "Process Control From an Economic Point of View", *Report Series in Quality and Productivity*, Report No. 42, Center for Quality and Productivity Improvement, University of Wisconsin, Madison, WI, February 1990.

[28] Lucas, James M., "The Design and Use of V-Mask Control Schemes", *Journal of Quality Technology*, Vol. 8 No. 1, January 1976.

[29] Lucas, James M., and R. Crosier, "Fast Initial Response for CUSUM Quality Control Schemse: Give Your CUSUM a Head Start", *Technometrics*, Vol. 24, No. 3, pp. 199-205, August 1982.

[30] Maguire, Edmund J., "SPC in the Small Company", *Annual Quality Congress Transactions*, Vol. 44, pp. 506-510, 1990.

[31] Montgomery, Douglas C., *Introduction to Statistical Quality Control, Second Edition*, John Wiley & Sons, NY, 1991.

[32] Montgomery, Douglas C., *Design and Analysis of Experiments*, Wiley Publishers, New York, 1984.

[33] O'Connell, Raymond G. Jr., "The Role of Doppler Ultrasound in Cardiac Diagnosis", *Hewlett-Packard Journal*, pp. 20-25, June 1986.

[34] Phadke, Madhav S., *Quality Engineering Using Robust Design*, Prentice Hall, Englewood Cliffs, NJ, 1989.

[35] Phadke, Madhav S. and Taguchi, G, "Selection of Quality Characteristics and S/N Ratios for Robust Design", *Conference Record, GLOBECOM 87 Meeting, IEEE Communicaitons Society*, Tokyo, Japan, pp. 1002-1007, November 1987.

[36] Rocke, David M., "Robust Control Charts", *Technometrics*, Vol. 31, No. 2, pp. 173-184, May 1989.

[37] Rocke David M., and H. Zhou, "Robust EWMA Control Charts", working paper last revised March 1992.

[38] Rocke, David M. "X-bar and R charts: Robust Control Charts", *The Statistician*, Vol. 41, pp. 97-104, 1992.

[39] Sachs, Emmanual, A. Ingolfsson, and A. Hu, "Run by Run Process Control: Combining SPC and Feedback Control", working paper to be submitted to *IEEE Transactions on Semiconductor Manufacturing*.

[40] Sachs, Emmanual, R. Guo, S. Ha, and A. Hu, "Process Control System for VLSI Fabrication", *IEEE Transaction on Semiconductor Manufacturing*, Vol. 4., No. 2, May 1991.

[41] Shewhart, Walter A., *Economic Control of Quality of Manufactured Product*, Van Nostrand Reinhold, Princeton, NJ, 1931.

[42] Taguchi, G., *Introduction to Quality Engineering*, Asian Productivity Organization, 1986.

[43] White, Edna M., and R. Shroeder, "A Simultaneus Control Chart", *Journal of Quality Technology*, Vol. 19, No. 1, pp. 1-10, January 1987.