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The use of strain gage technology to measure the torsional forces applied to a package while online.

presented by

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has been accepted towards fulfillment
of the requirements for

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--AN INSTRUMENTED BOTTLE --
THE USE OF STRAIN GAGE TECHNOLOGY TO MEASURE THE TORSIONAL FORCES APPLIED TO A PACKAGE WHILE ONLINE

By

William George Kilbridge

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ABSTRACT

--AN INSTRUMENTED BOTTLE --
The Use of Strain Gage Technology to Measure the Torsional Forces Applied to a Package while Online.

By

William George Kilbridge

The purpose of this research was to design, fabricate and test an instrumented package which, when placed in a production line could measure selected forces. This study focused on the measurement of torque exerted on a bottle during the application of a closure. Strain gages, adhered to an elastic member were used to measure these forces.

The study demonstrated that an instrumented bottle, once calibrated, can provide a stable and repeatable method for the measurement of application torque.

The vision for this instrumented bottle is to un-tether it, thus, enabling it to wirelessly transmit collected data to a system that will monitor or track machine function. The intent is to provide operations and maintenance staff with a tool that can provide information pertaining to machine performance.

To Lucy

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INTRODUCTION

Currently, there is a push in the production arena to move from the widely accepted preventative maintenance (PM) methods into a predictive maintenance (PdM) mode. Predictive maintenance moves away from task scheduling at specific intervals to the periodic measurement of machine function. The goal is to anticipate machine failure by data analysis, and provide the appropriate maintenance activity prior to failure. The United States Navy, an advocate of PdM, discovered in the submarine fleet that large amounts of time and resources were lost in performing unneeded preventive maintenance.[1] It is estimated that "U.S. industry needlessly squanders an excess of $200 billion each year on inadequate or unnecessary maintenance procedures."[2]

With advances in computer technology and controls, much of the packaging industry has moved to sophisticated control systems which, when properly applied, can improve machinery operation and product quality. These same controls have provided manufacturers with very powerful tools to improve machine maintenance through the collection of data. Error logs and down time histories are examples of collected data which, when analyzed, can be used by maintenance staff to improve machine performance through informed maintenance decisions.

There are, however, some machines or processes that cannot be reasonably integrated with these high-tech monitoring systems. In general, the limiting factor is price. Take for instance a large high-speed liquid filling line equipped with a 100 head filling and closing carousel. To equip each head to measure a force applied to the package would be prohibitively expensive. Packaging and production personnel currently have a few alternatives in these situations when online monitoring is not feasible. One alternative is to establish and perform a manual sampling plan to inspect product after it has been processed. A second alternative is to install an ancillary system that can divert product for automatic sampling. In either case, the system is functioning in a reactive mode, and generally only one attribute is monitored. Depending on the sampling frequency used by these systems, a machine may have the opportunity to produce a large quantity of out of tolerance product — in other words scrap — before the line personnel realize that there is a problem.

The vision for this research evolved from the observation that the above mentioned ancillary systems only provide a few pixels in the picture of overall machine performance. Upon this realization, the goal was set to develop an instrumented or "rigged" package that could be introduced into a packaging operation with the intent of measuring the forces experienced in the capping process. In theory, decisions regarding line operation and maintenance could be made proactively by comparing recorded measurements to a pre-established machine baseline.

Chapter 1

LITERATURE REVIEW

Many sources were used to find information for this research. The databases used included the following: PIRA, Dissertation Abstracts, and the United States Patent Office. There was a plethora of resources available in the Engineering and Materials disciplines to aid in the design of the "rigged" model. Unfortunately little information was found in journals or theses citing the use of an instrumented package intended to measure packaging machine/line performance.

In 1991, California State University–Long Beach utilized strain gauge technology to measure the torque counterforce in automobiles. The purpose of the study was to "design, fabricate, and evaluate a solid state torque measurement device that would operate in real time and be completely contained within a specific vehicle."[3] In this study, an instrumented torque rod was tested statically and dynamically. The collected torque data was used to determine/estimate engine horsepower without the use of a chassis dynamometer. Among the conclusions formulated, it was stated that "a solid state torque measurement device that operates in real time and can be completely contained within a vehicle can be made for a reasonable cost, and still maintain a high degree of correlation to true horsepower."[3]

In a 1996 presentation at the 42ND annual Institute of Electrical and Electronics Engineers Pulp and Paper Conference several methods of measuring torque in an elastic member were discusses. The methods included Bonded Strain Gage Direct Torque Sensors, Phase Shift Direct Torque Measurement Sensors, and Magneto-Elastic Direct Torque Sensors. It was stated that strain gauges "can be bonded to the surface of a machine element in such a way as to be sensitive to the principle strains and thereby the principle stresses. Knowing the calibrated measure of the principal stresses and the section area of the machine element, the reaction force in an element can be calculated."[4] The relationship between an applied moment (torque) and the stress/strain experienced by a shaft was discussed. The article states that " both (combined strain and shear stress) can be seen to be proportional to T, the applied torque."[4] "All practical torque sensors use the measurement of one or both of these elements (strain and or shear stress) as their means of deriving the torque transmitted by a machine element."[4]

A search of patents issued in the United States between 1979 and 1998 was performed. The keywords "packaging machinery" and "application torque" proved to be fruitful. The search revealed that, in at least two instances, commercial development has occurred in the area of online application torque measurement using an instrumented package.

Humphries and Sangster of England were granted patent number 5,319,984 on June 14th, 1994. The patent states that the aim of the invention was "to provide a remedy to the problem of loose caps or insufficiently tightened caps, and/or to the problem of over-tightened caps."[5] The device is described as follows:

"a device comprising a dummy body, shaped to perform as a container body in such machinery, an externally screw-threaded neck part having the form of the neck of a container which is capped by such machinery, a substantially rigid stem secured rigidly to the neck part and to the dummy body, at least one strain gauge which is bonded along the outside surface of the stem to provide an indication of a torque applied to the neck part, and electrical-signal generating means within the dummy body, in which the strain gauge is connected to the electrical-signal generating means to generate an electrical signal when the device is in use, which is indicative of the torque applied by such capping machinery to the neck part, whereby such an indication is obtained without rotational displacement of the neck part relative to the dummy body."[5]

The patent explained several details of the system, but did not provide any specifics regarding the strain gage positioning or placement. Conceptually, the method presented in the patent for measuring torque with a strain gage is the same as that discussed by Beihoff and many engineering texts – the strain exhibited by an elastic member is proportional to the applied force.

On May 16th, 1995 Trendel and Spencer were issued patent number 5,415,050 for their invention. The patent was assigned to Owens-Brockway Glass Container Inc. of Toledo, Ohio. The device was described as a "self-contained apparatus for measuring threaded closure application torque that includes a container-shaped enclosure having a threaded finish portion configured to receive a threaded closure."[6] Although the concept used by Trendel and Spencer utilizes strain gages, it is quite different from the method used by Humphries and Sangster. The patent states:

"In the preferred embodiment of the invention, the finish portion of the enclosure is mounted for rotation with respect to the remainder of the enclosure. A load sensor assembly is mounted within the enclosure and coupled to the finish portion of the enclosure for developing the electrical measurement signal as a function of torque applied to the finish portion of the enclosure with respect to the remainder of the enclosure. The electronic circuitry stores the maximum or peak value of the sensor signal as indicative of the torque applied to the closure. The stored signal is scaled for direct reading in units of torque, and may be reset by an operator for reinsertion through the closure application system."[6]

The above mentioned load sensor assembly is known in engineering texts as a transmission dynamometer. In short, thin bars, which are equipped with strain gages, couple the freely rotating finish shaft to the fixed base of the unit. The thin bars deflect under the applied force. The strain gages stretch or compress creating a change in resistance. The strain gage output is proportional to the applied load.

Although the above patents do not provide any data, they are important to note. A search of dissertations, theses, and journals regarding the use of instrumented packages intended to measure production line forces proved to be unproductive. The existence of patents, however, demonstrates that the premise is sound, and that there is potentially a need commercially for the type of online force measurement device proposed in this research.

Chapter 2

BACKGROUND INFORMATION

While developing the "rigged" bottle, many concepts and methods had to be learned. This chapter focuses on the concepts used in the development and testing of the test bottle.

Measurement

What is measurement? In it's most simple form; measurement is the process of "obtaining a quantitative comparison between a predefined *standard* and a *measurand*."[7] Measurement can be broken down into two methods: indirect and direct comparisons. Direct measurement uses a standard to determine the quantity present and indirect measurement methods utilize an input from the entity being measured. Indirect methods use a system that takes the input and "processes" it into a format that can be recognized or compared.[7] This study utilized an indirect method of measurement using resistance strain gages.

Calibration

The calibration of a measuring system is critical. If the data coming out of a system cannot be correlated to a known value, the system is useless. Another very important aspect of calibration is not only applying known values to a measurement, but also in demonstrating that the system can perform reliably. "At some point during the preparation of a measuring system, *known* magnitudes of input quantity must be fed into a the sensor-transducer, and the system's output behavior must be observed... this *calibration* procedure establishes the correct output scale for the measuring system."[7]

<u>Stress-Strain Relationship</u>

During axial loading, stress (σ) is defined as the ratio of force (F) to cross-sectional area (A):

$$\sigma = \frac{F}{A}$$

Strain (ε) is the ratio of a materials change in length (Δl) to original length (l):

$$\varepsilon = \frac{\Delta l}{l}$$

The stress-strain diagram describes the behavior of a material. The proportional limit of a material represents the point at which the deformation of a material makes the transition from being elastic (capable of returning to its' original length) to plastic (permanent deformation of the material). The slope of the linear portion of the stress-strain diagram is called the modulus of elasticity (represented by the symbol E). The modulus of elasticity is an indication of a materials stiffness. Robert Hooke in 1676 introduced a relationship between stress, strain, and the modulus of elasticity.[8] For a uniaxial state of stress the relationship, now called Hooke's Law, states that:

$$E = \frac{\sigma}{\varepsilon}$$

E = Modulus of Elasticity

σ = Stress

ε = Strain

Strain Gages

Strain gages are devices used to measure the change in length of a material as a load is applied. The underlying principle behind strain gages states that a change in electrical resistance will occur when an electrical conductor changes in length. Lord Kelvin first demonstrated this phenomenon in 1856 "Electrically conductive materials possess a strain/resistance relationship defined as the ratio of relative electrical resistance change of a conductor to the relative change in its length." Resistance for any given electrical conductor is represented by the following relationship[9]:

$$R = \frac{\rho l}{A}$$

R = Resistance

ρ = Resistivity

l = Length

A = Cross Sectional Area

When a conductor is placed in tension, the above relationship states that the resistance will increase due to an increasing length and a reduced cross sectional area due to Poisson's effect. The relationship is opposite when a conductor is placed in compression – the conductor is shortened and the cross sectional area increases.[10]

Using a "grid of fine resistance wire bonded to a test surface as a means of measuring strain" was described in the late 1930s by Edward Simmons at the California Institute of Technology.[10] Today, strain gages come in many shapes and sizes, but the most prevalent is the foil type resistance strain gage. The foil type gage is a laminated structure of very thin foil on a backing material, usually polyamide. A photo etching process is used to create the fine gage grid. Figure 1 is an illustration of a typical general-purpose strain gage.

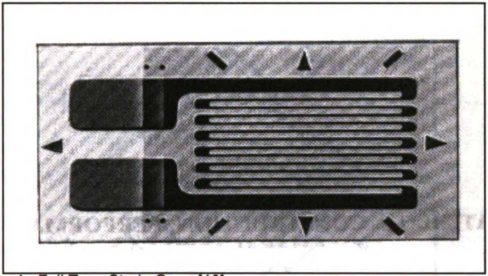

Figure 1. Foil Type Strain Gage.[10]

Due to various material properties and test conditions, several gage characteristics must be considered during the strain gage selection process. Some of these characteristics include gage factor, resistance, temperature effects, operating temperature range, and fatigue life.[10]

Wheatstone Bridge

The majority of applications utilizing strain gages incorporate a circuit called a Wheatstone bridge. S.H. Christie devised the circuit in 1833.[7] The purpose of a bridge circuit is to convert very small resistance changes – as commonly seen in strain gages – into a voltage that can be amplified and read on a volt meter or other data acquisition device. The bridge is made up of four arms each containing a resistor. The resistors are labeled R1, R2, R3, and R4. The resistors can take the form of actual resistors, or resistive elements such as strain gages and thermistors. A power source (V_{in}) supplies the bridge with power, and the change in voltage (V_{out}) feeds the data acquisition device. Figure 2 is a simple illustration of a Wheatstone Bridge circuit.

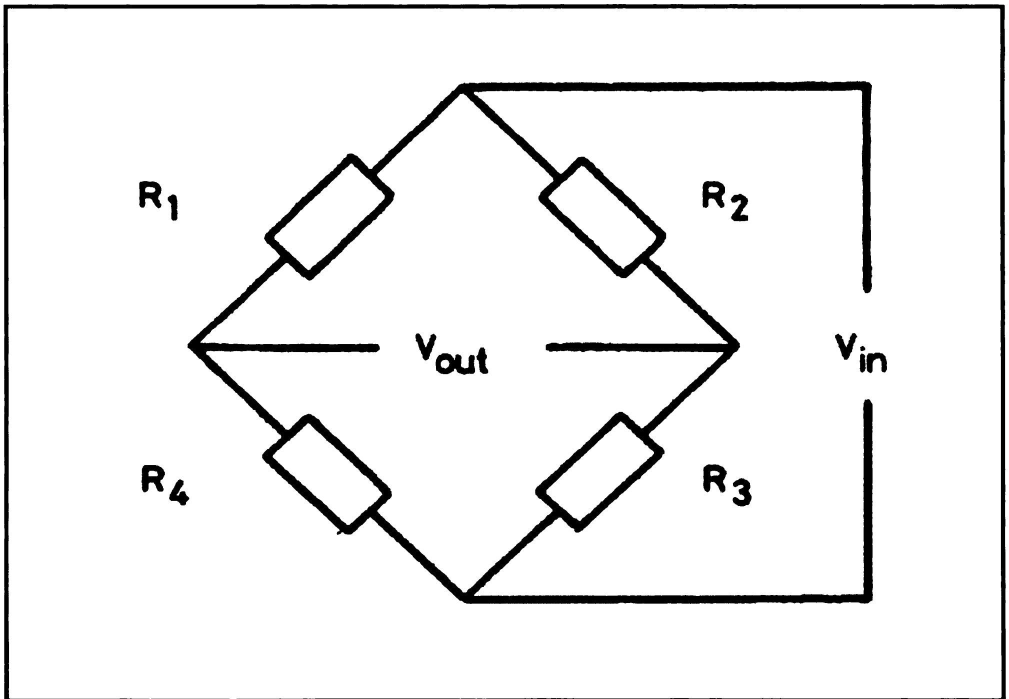

Figure 2. Wheatstone Bridge Circuit.[10]

In a normal state, a bridge circuit is balanced, i.e., V_{out} is zero when R1/R4 = R2/R3. A change in resistance in one of the arms, for instance R1, will create an unbalanced system producing a voltage across V_{out}.[10] If the change in voltage is displayed on a voltmeter, the strain can be calculated. If the bridge circuit is connected to an instrument specifically intended for the measurement of strain, the instrument circuitry calculates and displays the strain. The bridge circuit can be configured in several ways when using strain gages: quarter bridge, half bridge, and full bridge. A quarter bridge places a strain gage in one of the four bridge arms. The half bridge places two strain gages in two of the four bridge arms. The full bridge circuit replaces all four of the resistors in the bridge circuit with strain gages. The application to be studied will dictate which circuit configuration is appropriate.

Torsion Formula for a Thin Walled Tube

Hooke's law can be used to calculate stress and strain in a material when torsional forces are applied. A cylindrical body in torsion experiences shear stress (τ) and shear strain (γ). Shear stress is considerably different than normal stress. Unlike normal stress, the acting force on a body is not perpendicular to its' plane. The shear force orientation is tangential to the bodies' plane resulting in a "sliding" of material on one side of the plane across the material on the other side.[8] Figure 3 is a simple illustration of shear strain.

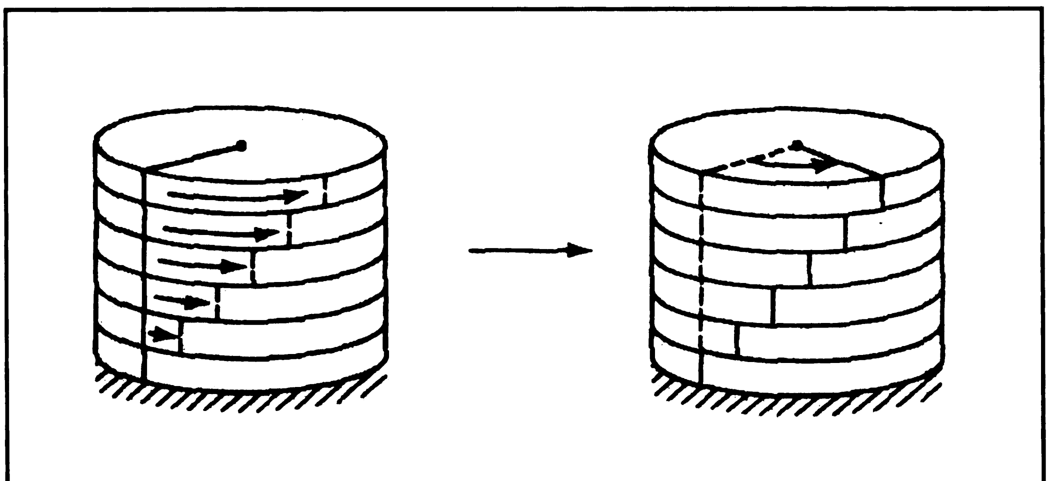

Figure 3. Simple Illustration of Shear Strain.[11]

The maximum shear stress (τmax) in a body is determined by the following equation:

$$\tau max = T * \frac{C}{J}$$

T = Applied torque (Force x Lever Arm)
J = Polar moment of inertia
C = Cylinder/Tube Radius

The polar moment of inertia (J) is determined by the following equation:

$$J = \frac{\pi * (do^4 - di^4)}{32}$$

do = Ouside Diameter
di = Inside Diameter

When the properties of a material (E and ν) are known, it is possible to calculate both shear stress and shear strain based on an applied torsional load. These theoretical calculations can be used to indicate whether a measured strain value is appropriate, or expected based on material properties.

Shear strain (γ) can be calculated using the following formula:

$$\gamma max = \frac{2 * (1 + \upsilon) * \tau}{E}$$

ν = Poissons Ratio

E = Modulus of Elasticity

τ = Shear Stress

Due to the positioning of the strain gages on the transducer shaft, the theoretical value for shear strain will be half as large as the strain indicated by a full bridge circuit. This is due to the 45 degree positioning of the gages on the transducer shaft. At 45 degrees the tensile and compressive strains are half of the theoretical shear strain value. Thus, with four active strain gages in the full bridge circuit, the actual output ends up being twice that of the theoretical value (4 gages x 0.5).[12]

Chapter 3

DESIGN AND FABRICATION

A variety of engineering texts were used to aid in the design of the test bottle. Several models were designed and built during this project. Each model generation made improvements on the previous. Several objectives guided the design of the test bottle. The design objectives included the following: the test bottle must be capable of being instrumented; the design must measure application torque, the bottle must be stable, i.e., it must provide repeatable results; the design must be capable of being integrated into different package geometries; and it must be compatible with the available machinery in the Michigan State University School of Packaging production lab.

The model consists of three components: the bottle housing, the finish, and the instrumented shaft.

The Bottle Housing

The bottle housing consists of three basic parts: two end disks, and the cylindrical body. The end disks are 3/8-inch thick Lucite flat stock. Figure 4 is an illustration of the two end disks. The disks were turned to a diameter that produced a press fit (approximately 2.5 inches) into the cylindrical body. Both end disks had a 7/8-inch diameter hole bored through the center. The bottom disk had two 8-32 setscrew holes drilled and tapped through the side of the disk 90 degrees apart. The purpose of the setscrews was to hold the end of the transducer shaft in a fixed position.

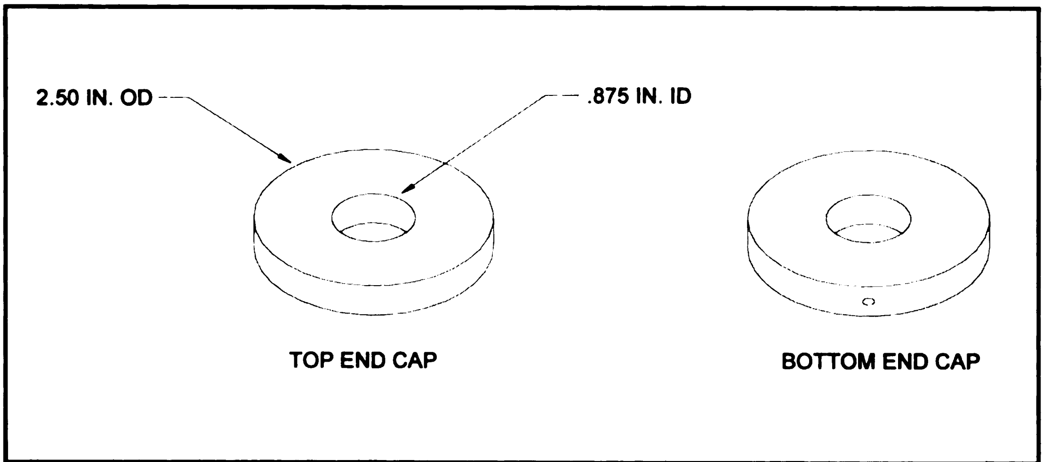

Figure 4. Test Bottle End Caps.

The cylindrical body consisted of a 3-inch diameter Lucite tube with a ¼-inch wall thickness. Figure 5 is an illustration of the Lucite test bottle body.

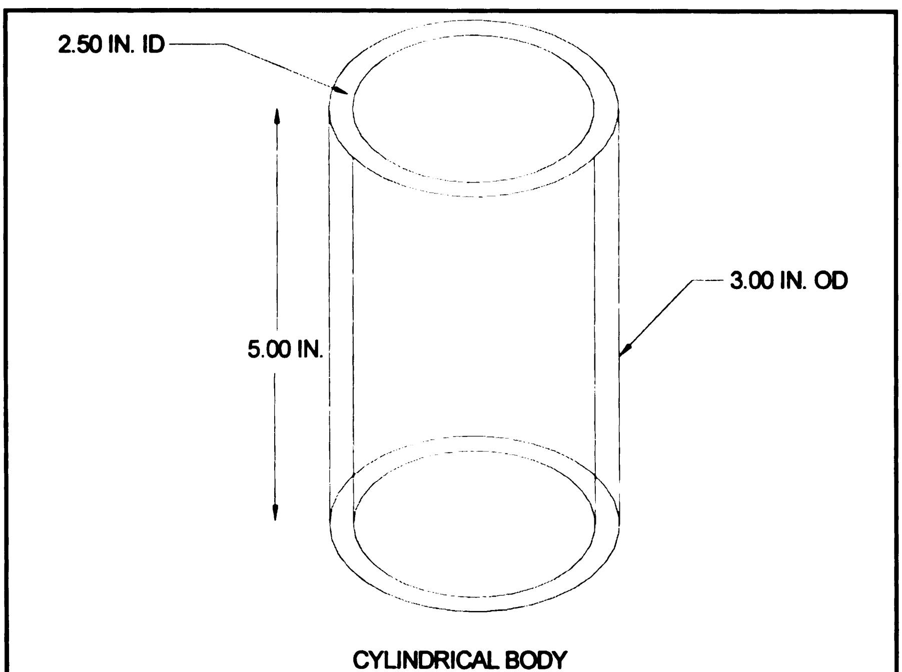

Figure 5. Test Bottle Body.

The tube was 5 inches long. The function of the cylindrical body was to provide a structure for the model and to protect the otherwise vulnerable strain gages on the transducer shaft. The size of the tube was arbitrarily chosen; a variety of sizes and shapes could have been selected to produce equivalent results.

The Bottle Finishes

The intent of the finish design was to provide a method of testing both static and dynamic forces. Thus, 2 separate finishes were developed; one for static and one for dynamic testing. The design allowed the finishes to be easily interchangeable.

The static test finish had a clearance hole for a ¼-20 flat head bolt through its center, and two diametrically opposed 1/8-inch pinholes on a 0.600-inch diameter. The static test finish had a square profile. Figure 6 illustrates the static test finish. The static finish mated with a 4 inch Lucite disk intended to provide a consistent lever arm length.

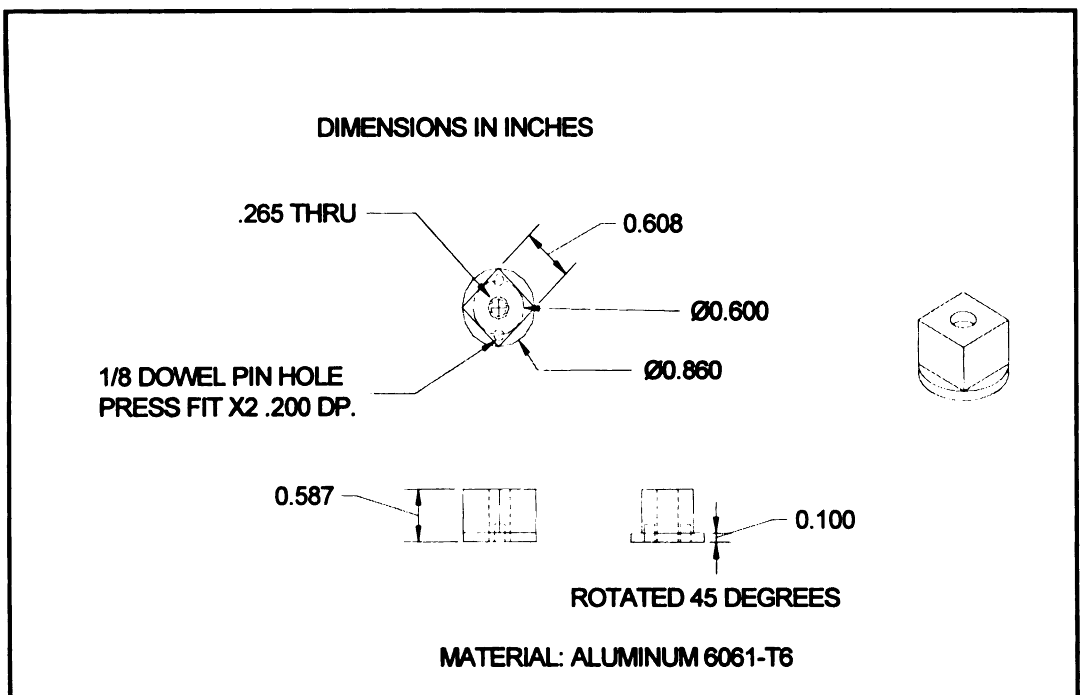

Figure 6. Static Test Finish.

The dynamic test finish had a clearance hole for a ¼-20 flat head bolt through its center, and two diametrically opposed 1/8-inch pinholes on a 0.600-inch diameter. The profile of the dynamic test finish was that of a 28-400 bottle. Figure 7 is an illustration of the dynamic test finish. This finish allowed for the application of actual 28-400 continuous thread (CT) closures using capping machinery.

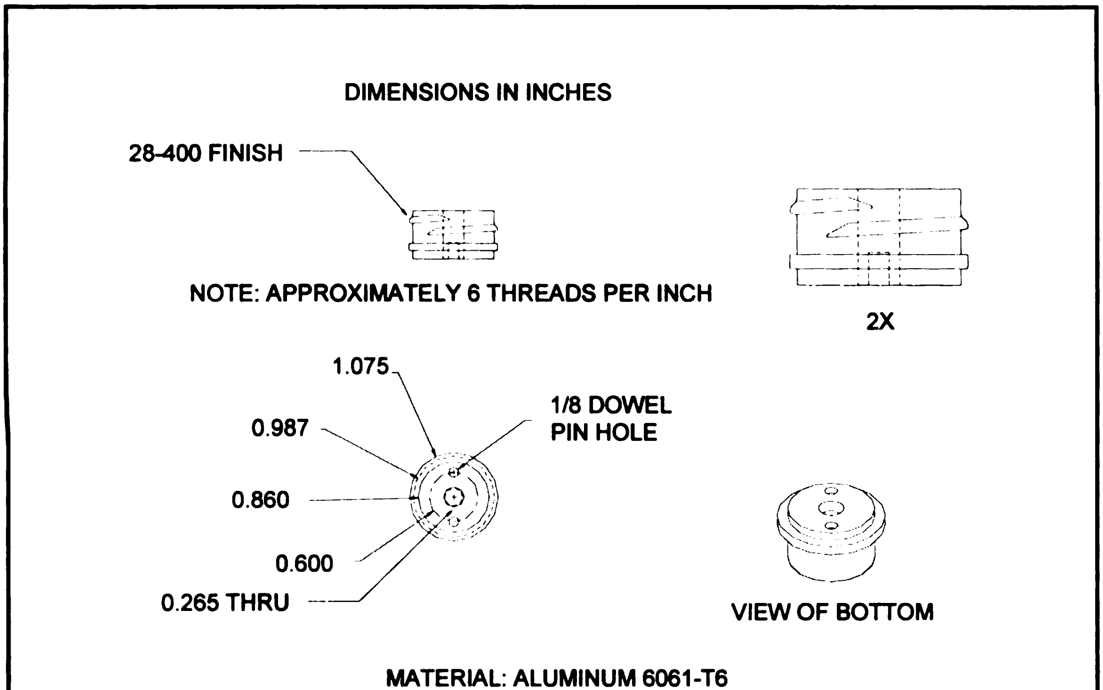

Figure 7. Dynamic Test Finish.

<u>The Instrumented shaft</u>

The heart of the test bottle was the transducer shaft. Transducers operate by using "a spring element which is simply a piece of suitable metal designed to deform elastically and linearly when the desired parameter (force) is applied to it." It "has strain gauges attached to it so that the deformation is converted into an electrical output."[13] The electrical output is calibrated using known applied loads.

The elastic element was a 7/8-inch diameter aluminum tube with a wall thickness of 0.062 inches. The tube had a flanged plug made for each end. The plugs were epoxied and pinned into place. The top plug had a ¼-20-threaded hole through its center, and two diametrically opposed 1/8-inch pinholes on a 0.600-inch diameter. The total length of tube (plugs included) was 5.500 inches. Figure 8 is an illustration of the instrumented shaft and plugs.

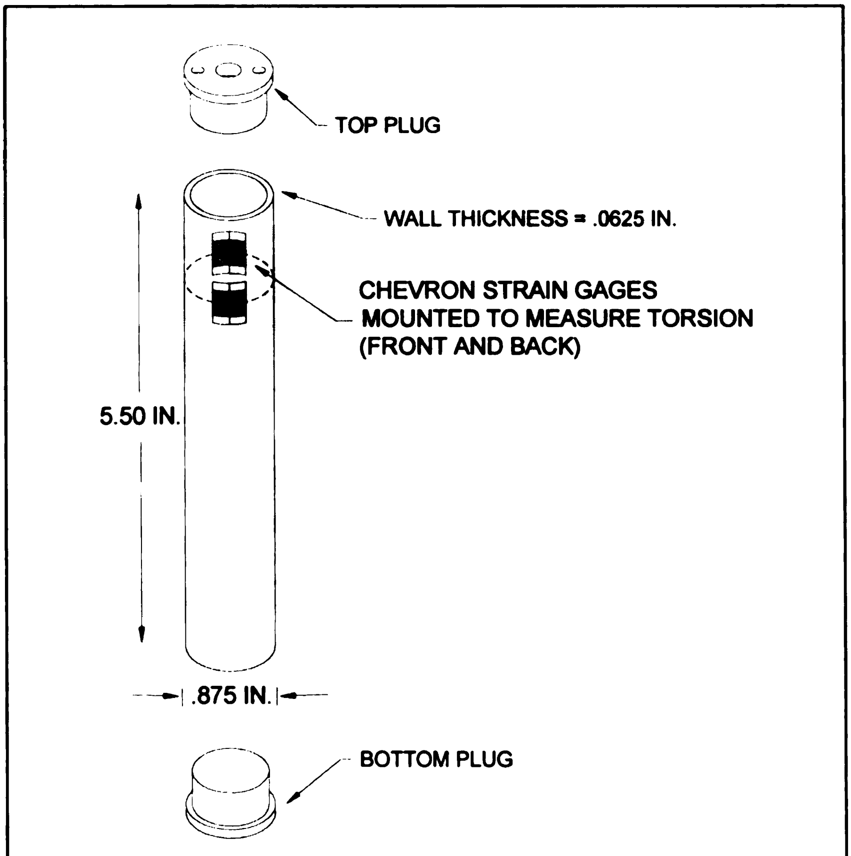

Figure 8. The Instrumented Shaft and Plugs.

The intent of the instrumented shaft was to measure both the torque and top load compression experienced by the test bottle during filling and closing. To accomplish the measurement of both forces, two independent circuits were used; one sensitive only to torsional loading, and one sensitive to compression.

The circuit for measuring torsion utilized special 350-ohm strain gauges designed for that purpose. The circuit formed a full bridge with two strain gages containing a total of four gage elements mounted in a chevron pattern. In a chevron pattern, the gage elements were positioned at 45 degrees to the axis of the tube, thus taking advantage of the principle axis of strain on the surface of the tube. The two pair of gages were mounted on opposite sides of the tube. Figure 9 below provides a simplified illustration of the strain gage orientation, and

Figure 10 is a schematic of the Wheatstone Bridge circuit.

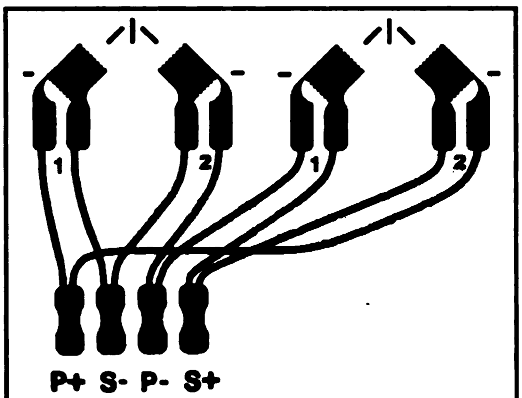

Figure 9. Instrumented Shaft Gage Orientation.[14]

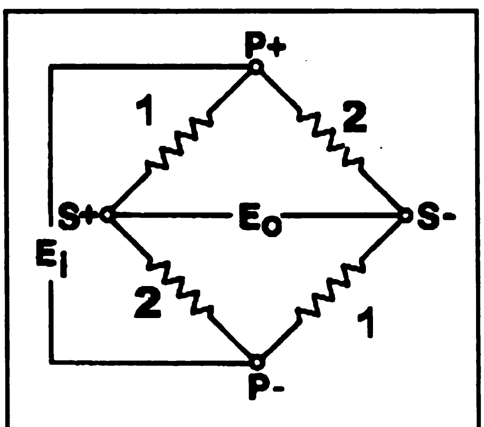

Figure 10. Wheatstone Bridge Schematic.

The gages were positioned in this manner because “when four gages are mounted on the shaft in pairs directly opposite each other, and in the directions of both principle axes, the bridge output will be: directly proportional to the applied torque, independent of axial thrust, independent of bending, and independent of temperature changes.”[15] The gages were mounted on the shaft 4.5 inches from the bottom of the test bottle.

Figure 11, below, is a photograph of the final bottle design.

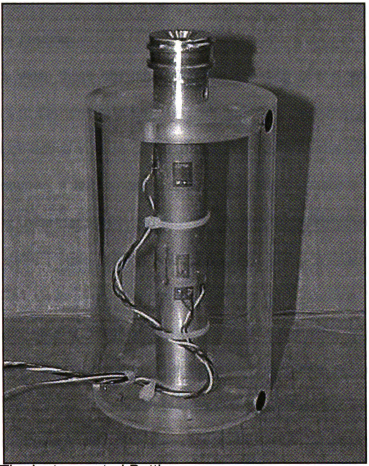

Figure 11. The Instrumented Bottle.

Chapter 4

METHODS

To accurately simulate realistic operation, the instrumented bottle had to be tested both statically and dynamically. The static tests were required to demonstrate that the strain gages performed properly. The dynamic tests provided the opportunity to see how the instrumented bottle performed while being loaded at realistic strain rates.

Static Torque Testing

There were three objectives for static testing of the test bottle. The first objective was to demonstrate that the installation of the strain gages was correct. The second objective was to develop a mathematical relationship (the equation of a line) between a known applied load and the transducer output. The final objective was to demonstrate that the mathematical relationship was accurate.

The static torque testing was performed using a method similar to that used in ASTM D 3474-80 "Standard Practice for Checking the Calibration of Torque Meters used in Packaging Applications". A fixture was built to hold the bottle in a fixed vertical position. A special finish for the test bottle was designed for this test (Figure 6). The finish mounted directly onto the transducer shaft and a four-inch diameter Lucite disk mated with the finish. A length of wire rope was fixed to, and wrapped around the outside diameter of the disk. The wire passed over a pulley and had a loop in the end. A dead load was hung from the loop in one pound increments. The following equation was used to determine the torque applied to the bottle:

$$T = FL$$

T = Torque
F= Magnitude of Force (pounds)
L = Lever Arm (2 inches)

A Measurements Group P-3500 portable strain indicator was used to display the strain experienced by the transducer shaft. The strain indicator was wired as a full bridge circuit and balanced at zero when unloaded. The output of the strain indicator was in microstrain ($\mu \times 10^{-6}$) units; the standard measure of strain when using strain gages. Weight was hung from the test bottle starting at one pound and increasing in one pound increments up to twelve pounds resulting in a range from 2 to 24 torque inch pounds (the four-inch diameter Lucite disk produced a two-inch lever arm). The strain data was collected at each step. Five trials at each weight increment were performed.

The data were plotted, a linear regression was performed, and an equation of the line was determined. To validate the equation, thirty unknown weights were hung from the bottle. The strain values were applied to the equation to determine the unknown applied torque. The unknown weight was then weighed on a bench-top scale and compared to the calculated measure.

Dynamic TorqueTesting

The objective of the dynamic testing was to determine a relationship between an application torque and the output of the test bottle.

A bench top Zalkin capping machine was used to apply the 28-400 CT closures to the test bottle. The Zalkin capper featured a magnetic torque-limiting head which would "slip" once the set torque was reached. The machine was fitted with variable speed controls for both head rotation and vertical displacement. An LED output displayed capper spindle speed in revolutions per minute.

A fixture was built to hold the test bottle securely on the machine base. The static testing finish on the test bottle was replaced with the 28-400 threaded finish. The machine cycle — spindle speed and vertical displacement — was set up to ensure that the capper head would not slip on the cap as the maximum torque was reached. It was initially noted that, at high spindle speeds and high torque settings, the head could slip on the cap, resulting in erroneous data. The spindle speed was set at 90 RPM (2.0 on the potentiometer dial), and the vertical displacement speed was set at 2.5 on the potentiometer. The vertical position of the head was set at 9.25 inches from the base. These settings proved to be acceptable across the torque range being measured. Figure 12 is a photograph of the dynamic torque test setup.

As mentioned, the capper head was fitted with a magnetic clutch to limit torque. The applied torque was adjusted by increasing the penetration between the magnetic field in the fixed head body and a movable magnetic ring. The application torque increased as the penetration of the inner ring into the head body increased. The manufacturer supplied a setup gage consisting of four torque settings; 12, 17, 22, and 27 torque inch pounds. The dynamic tests were performed using these settings.

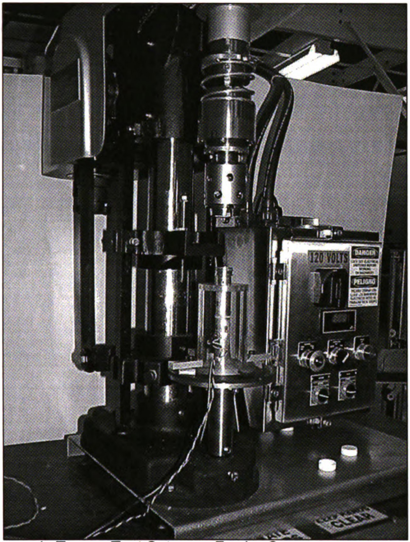

Figure 12. Dynamic Torque Test Setup on Fowler Capper.

The Measurements Group M-3500 Strain indicator was wired as a full bridge. A Measurements Group M-3650 Peak Read Indicator was wired to the M-3500 to record and hold the peak strain values reached during the capping cycle.

A sample of 50 measurements was taken at each torque setting and a mathematical relationship (the equation of a line) was determined. To validate the relationship, the machine was run at randomly selected torque settings using ten caps at each setting.

Chapter 5

RESULTS

Static Torque Testing

The calibration process for static torque demonstrated that the test bottle performed in a very linear fashion within the range of interest. Figure 13 illustrates the calibration curve produced from the collected strain data.

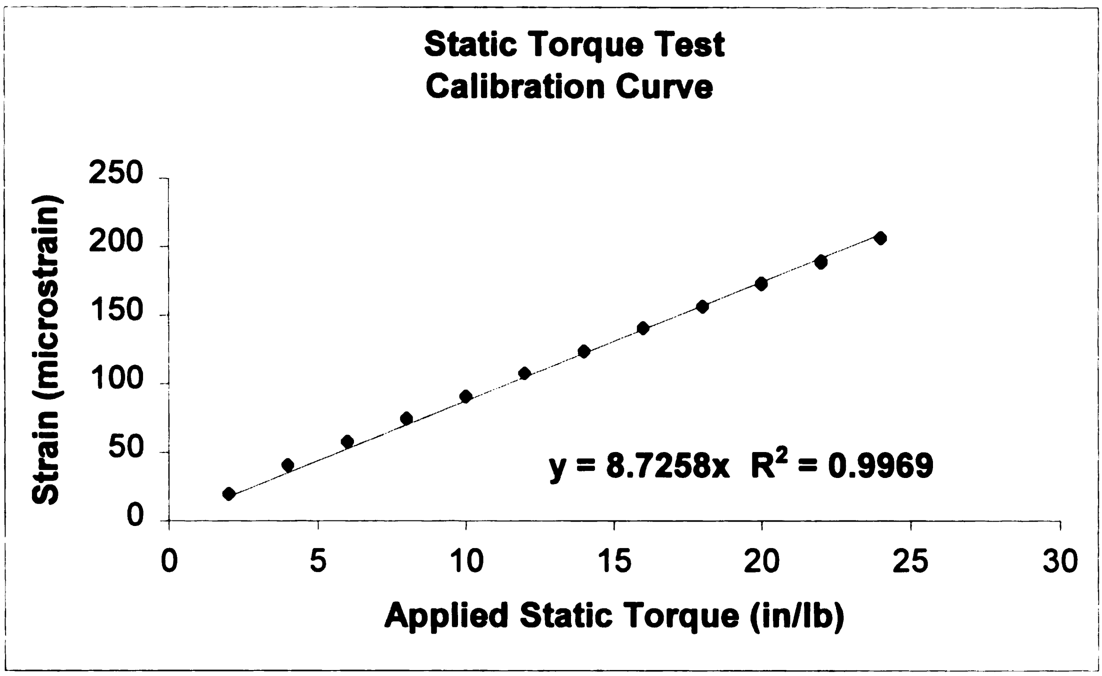

Figure 13. Calibration Curve from the Static Torque Test.

To validate that the recorded strain values were appropriate the Modulus of Elasticity (E) of the transducer shaft was calculated using the collected strain data and shaft geometry. Assuming a Poisson's ratio of 0.3 the calculation yielded an average E of 9,501,024 psi. This calculation demonstrated that the shaft performance was characteristic of aluminum, which has a documented E of approximately 10,000,000 psi.

A 95% confidence interval was determined using the calibration data. A test of thirty random torque values was performed to validate the calibration curve. The collected strain data were applied to the calibration equation to predict the applied torque. Figure 14 illustrates that the predicted torque data from the calibration curve fell within the 95% confidence interval.

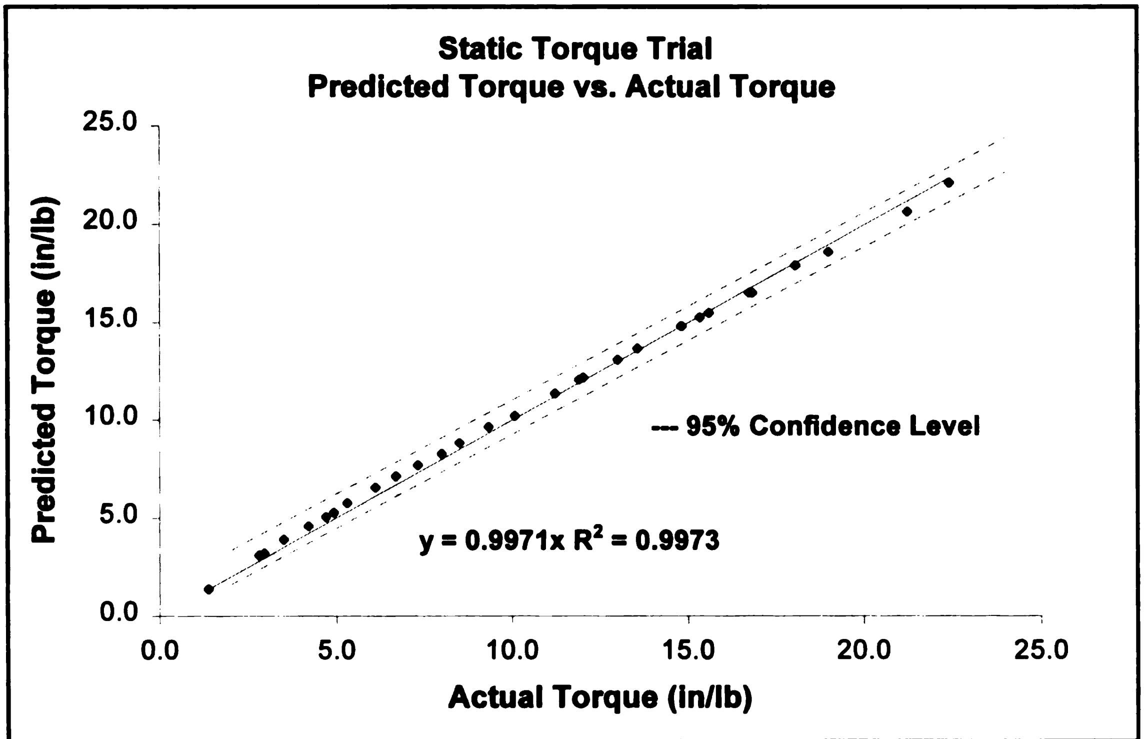

Figure 14. 95% Confidence Interval for the Static Torque Test.

Dynamic Torque Testing

Several dynamic torque trials were run prior to collecting the final data. The early trials provided the opportunity to gain a further understanding of the machine operation and adjustments. The most appropriate machine configuration was determined based on the information gathered in the trials.

A single factor Analysis of Variance (ANOVA) was used to determine if the data collected at a given application torque came from the same population. ANOVA is a statistical method which allows the researcher to determine whether there is "equality or nonequality" between means.[16] A single factor ANOVA has a single variable (in this case the set application torque) "which may influence the dependant variable Y."[16] The null hypotheses for the dynamic torque testing stated the following:

H_o: $x_{\text{sample } 0} = x_{\text{sample } 1} = x_{\text{sample } 2} = x_{\text{sample } 3} = x_{\text{sample } 4} = x_{\text{sample } 5}$

H_a: The six means are not equal.

If the p-value is less than 0.05, the null hypothesis must be rejected. If the p-value is greater than 0.05, the null hypothesis must be accepted – suggesting that the samples are statistically equivalent based on the criteria and methods used.

Table 1 summarizes the ANOVA for the initial dynamic torque trial. In this trial, the P-value for torque settings 17 and 22 torque inch pounds is less than 0.05 indicating a statistical difference between sample means.

The test methods used in the trial were evaluated, and two potential causes of variability were identified: the changeover between torque settings, and spindle orientation. Upon examination of the changeover process, it was determined that variation in setting the torque head (due possibly to backlash between the inner and outer magnets) could have attributed to the differences between samples. The setup process was modified to ensure that the changes between torque settings were more consistent. The orientation of the spindle at cycle start was questioned as well. To eliminate variation, the spindle was placed in the same position prior to the start of each machine cycle.

Table 1. ANOVA for Initial Dynamic Torque Test (α = .05)

	Source of Variation	SS	df	MS	F	P-value	F crit
Torque Setting 12	Between Groups	15.07	5	3.01	0.952	0.456	2.400
	Within Groups	158.36	50	3.17			
	Total	173.43	55				
Torque Setting 17	Between Groups	64.62	5	12.92	3.927	0.005	2.413
	Within Groups	154.67	47	3.29			
	Total	219.28	52				
Torque Setting 22	Between Groups	56.61	5	11.32	4.268	0.003	2.393
	Within Groups	137.96	52	2.65			
	Total	194.57	57				
Torque Setting 27	Between Groups	22.08	5	4.42	2.255	0.064	2.413
	Within Groups	92.03	47	1.96			
	Total	114.11	52				

Table 2 summarizes the ANOVA for the data collected after the changes to the setup procedure had been made. In this experiment, all of the P-values were above 0.05, indicating that all of the sample means were equivalent based on the methods and criteria used for the test.

The calibration curve from the data collected in the revised dynamic torque test is illustrated in Figure 15. As seen in the static torque tests, the relationship between the dynamic torque setting and recorded strain was very linear.

A 95% confidence interval for the calibration data was determined to illustrate the consistency between it, the initial calibration data, and the test data. The calibration curve was used to calculate a predicted torque based on the recorded strain from fifty samples taken from each of the four available torque settings.

Table 2. ANOVA for the Dynamic Torque Test (α = .05) – Revised Procedure.

	Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Torque Setting 12	Between Groups	20.72	5	4.14	1.431	0.220	2.311
	Within Groups	272.12	94	2.89			
	Total	292.84	99				
Torque Setting 17	Between Groups	23.01	5	4.60	1.075	0.379	2.311
	Within Groups	402.30	94	4.28			
	Total	425.31	99				
Torque Setting 22	Between Groups	27.04	5	5.41	1.942	0.095	2.311
	Within Groups	261.72	94	2.78			
	Total	288.76	99				
Torque Setting 27	Between Groups	1.97	5	0.39	0.116	0.989	2.311
	Within Groups	318.78	94	3.39			
	Total	320.75	99				

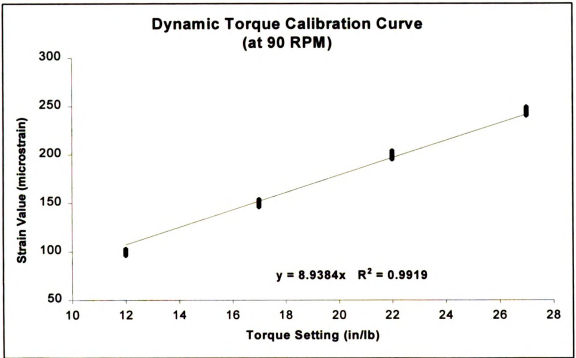

Figure 15. Calibration Curve for Dynamic Torque Test – 90 RPM

Figure 16 illustrates that the predicted torque – calculated using the calibration curve – fell well within the 95% confidence interval.

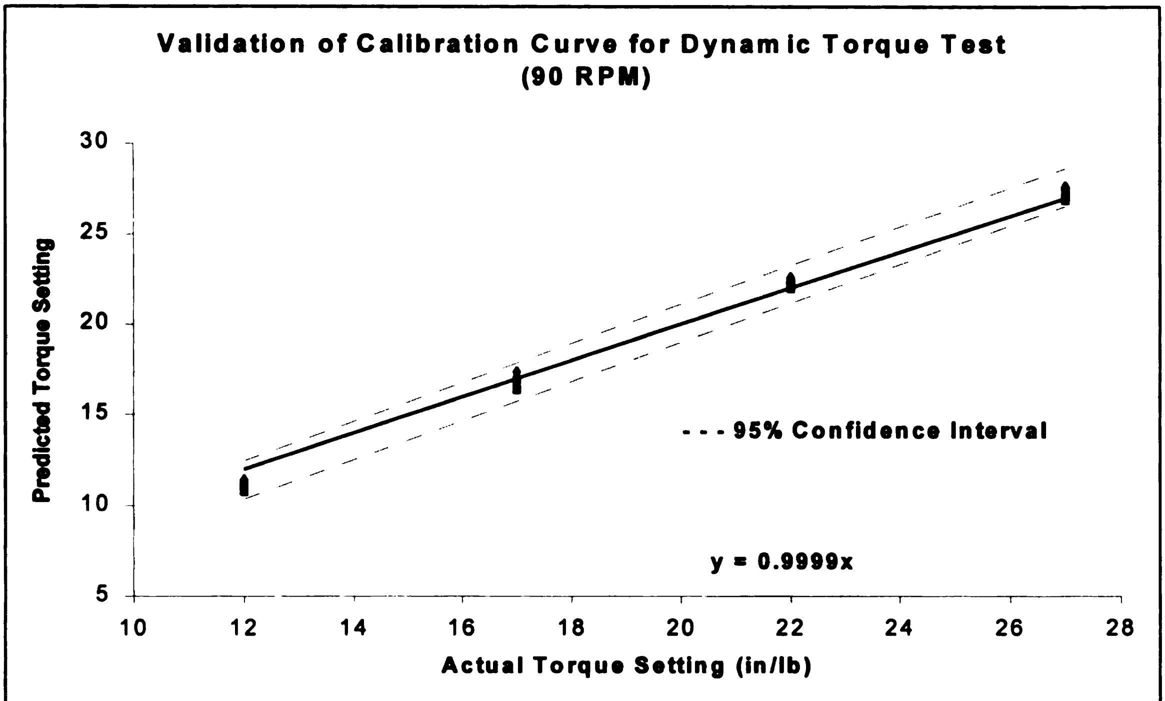

Figure 16. Validation of Calibration Curve for Dynamic Torque Test.

A calculation was performed to determine if the rate of loading had the potential to produce elevated recorded strain in the shaft due to wave propogation. The following calcualtion determines wave speed through aluminum:

$$c = \sqrt{\frac{E \times g}{\alpha}}$$

c = wave speed in (in/sec)

E = Modulus of Elasticity

g = gravity

α = material density (lb/in^3)

According to the wave speed equation it was determined that waves travel through aluminum at a rate of approximately 195,595 inches per second. This value is orders of magnitudes higher than the rate at which the shaft is loaded in practice. Based on this calculation, wave propagation through the instrumented shaft should not have any effect on the recorded strain values.

Chapter 6

CONCLUSION

This research demonstrated that strain gages can be incorporated into an instrumented package with the intention of measuring the forces experienced when introduced to a packaging machine. The application and selection of an elastic member (the component that experiences the applied force) must be carefully considered. In this project, a circuit was applied to an elastic member (the instrumented shaft) with the assumption that it could provide an accurate strain measurement under an applied force. The force under study was the torque experienced during the application of a continuous thread (CT) closure.

The circuit performed in a very stable fashion. The behavior of aluminum at elevated strain rates was examined. The relationship between applied torque and indicated strain was linear and repeatable in both static and dynamic situations. Several trials were run at various torque settings. With the aid of statistical analysis, it was determined that the collected data from the various trials were statistically equivalent, thus, they demonstrated stability.

The primary objective of this research was satisfied. A method to measure a force online with an instrumented package was successfully developed and tested.

Limitations of the Research

Throughout this study, attempts were made to ensure that the designs and tests were representative of actual production issues. The simple cylinder selected as the bottle body was chosen because a real package system or geometry was not available. In choosing an elastic member, an effort was made to ensure that it, with some reinforcement, could be applied to an actual package geometry.

The Fowler capper used in this study is only one of many methods available to apply CT closures. The results from this test can only be applied to this type of machine. The instrumented bottle should be tested on other capping devices to determine if it can provide useful information regarding the application of closures in other machines.

Areas for Future Study

Further study should be performed to identify additional methods of force measurement that can be incorporated into the structure of a rigged bottle. Load cells, thermocouples, and accelerometers are just a few of the possible measurement devices that could be included in an instrumented package.

Additional work is required to identify methods that can be used to untether the instrumented bottle, thus, allowing wireless transmission of strain data. Radio telemetry and infrared data transmission are two potential technologies. By removing the constraint of wires, an instrumented package could be conveyed freely through the various stations of a packaging line to measure forces as it moved.

APPENDICES

APPENDIX A

EQUATIONS

Equation for Torque:

$$\boxed{T = FL}$$

T = Torque

F= Magnitude of Force

L = Lever arm

Equation for Polar Moment of Inertia (J):

$$\boxed{J = \frac{\pi * (do^4 - di^4)}{32}}$$

do = Ouside Diameter

di = Inside Diameter

π = 3.1487

Equation for Shear Strain (γ):

$$\boxed{\gamma max = \frac{2 * (1 + \upsilon) * \tau}{E}}$$

ν = Poissons Ratio

E = Modulus of Elasticity

τ = Shear Stress

Equation for Modulus of Elasticity in Torsion of Thin Wall Cylinder:

$$\boxed{E = \frac{[32 * (1 + \nu) * (T) * (do)]}{[\gamma * \pi * (do^4 - di^4)]}}$$

APPENDIX B

STATIC TORQUE TEST DATA

Table 3. Static Torque Test Data.

Applied Load		Observed Strain (microstrain)					AVE	STD.
Weight (lbs.)	Torque (in/lb)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5		
1	2	19	20	20	20	19	19.6	0.55
2	4	40	41	41	40	40	40.4	0.55
3	6	58	58	57	57	57	57.4	0.55
4	8	75	75	74	74	74	74.4	0.55
5	10	91	91	91	90	90	90.6	0.55
6	12	108	107	107	107	107	107.2	0.45
7	14	124	124	123	123	123	123.4	0.55
8	16	141	140	140	140	140	140.2	0.45
9	18	157	156	156	156	156	156.2	0.45
10	20	174	173	172	173	172	172.8	0.84
11	22	190	190	189	189	188	189.2	0.84
12	24	207	207	206	206	206	206.4	0.55

Table 4. Linear Regression For Static Torque Test.

Regression Statistics	
Multiple R	0.998
R Square	0.997
Adjusted R Square	0.906
Standard Error	3.318
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	1	39770.614	39770.61	3612.43	3.95E-14
Residual	11	121.103	11.009		
Total	12	39891.717			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	8.7258	0.0651	134.0951	0.0000	8.582	8.8691	8.5826	8.8691

Table 5. Calculation of Modulus of Elasticity Based on Static Torque Data.

Torque (in/lb)	Observed Strain (microstrain)	Observed Strain (in/in)	Calculated Modulus (psi)
2	19	0.000019	9,046,400
4	40	0.00004	8,594,080
6	58	0.000058	8,890,428
8	75	0.000075	9,167,019
10	91	0.000091	9,444,044
12	108	0.000108	9,548,978
14	124	0.000124	9,702,994
16	141	0.000141	9,752,148
18	157	0.000157	9,853,086
20	174	0.000174	9,878,253
22	190	0.00019	9,951,040
24	207	0.000207	9,964,151
2	20	0.00002	8,594,080
4	41	0.000041	8,384,468
6	58	0.000058	8,890,428
8	75	0.000075	9,167,019
10	91	0.000091	9,444,044
12	107	0.000107	9,638,221
14	124	0.000124	9,702,994
16	140	0.00014	9,821,806
18	156	0.000156	9,916,246
20	173	0.000173	9,935,353
22	190	0.00019	9,951,040
24	207	0.000207	9,964,151
2	20	0.00002	8,594,080
4	41	0.000041	8,384,468
6	57	0.000057	9,046,400
8	74	0.000074	9,290,897
10	91	0.000091	9,444,044
12	107	0.000107	9,638,221
14	123	0.000123	9,781,880
16	140	0.00014	9,821,806
18	156	0.000156	9,916,246
20	172	0.000172	9,993,116
22	189	0.000189	10,003,691
24	206	0.000206	10,012,521
2	20	0.00002	8,594,080
4	40	0.00004	8,594,080
6	57	0.000057	9,046,400

8	74	0.000074	9,290,897
10	90	0.00009	9,548,978
12	107	0.000107	9,638,221
14	123	0.000123	9,781,880
16	140	0.00014	9,821,806
18	156	0.000156	9,916,246
20	173	0.000173	9,935,353
22	189	0.000189	10,003,691
24	206	0.000206	10,012,521
2	19	0.000019	9,046,400
4	40	0.00004	8,594,080
6	57	0.000057	9,046,400
8	74	0.000074	9,290,897
10	90	0.00009	9,548,978
12	107	0.000107	9,638,221
14	123	0.000123	9,781,880
16	140	0.00014	9,821,806
18	156	0.000156	9,916,246
20	172	0.000172	9,993,116
22	188	0.000188	10,056,902
24	206	0.000206	10,012,521
		Average E	9,501,024

Table 6. 95% Confidence Interval Calculation for Static Torque Test.

Setting						Strain			Lower	Upper
x	$[x_i - x]^2$	A	B	C	D	y	$[y_o - y]$	$[y_o - y]^2$	Limit	Limit
2	121.00	76.14	82.48	-830.85	7.39	19.60	-95.22	9066.21	1.21	2.97
4	-9.00	76.14	82.48	-649.35	7.39	40.40	-74.42	5537.84	3.59	5.35
6	-7.00	76.14	82.48	-501.01	7.39	57.40	-57.42	3296.67	5.54	7.30
8	-5.00	76.14	82.48	-352.67	7.39	74.40	-40.42	1633.51	7.49	9.25
10	-3.00	76.14	82.48	-211.31	7.39	90.60	-24.22	586.45	9.34	11.11
12	-1.00	76.14	82.48	-66.46	7.39	107.20	-7.62	58.01	11.25	13.01
14	1.00	76.14	82.49	74.90	7.39	123.40	8.58	73.67	13.10	14.87
16	3.00	76.14	82.49	221.49	7.39	140.20	25.38	644.31	15.03	16.79
18	5.00	76.14	82.49	361.10	7.39	156.20	41.38	1712.58	16.86	18.62
20	7.00	76.14	82.49	505.95	7.39	172.80	57.98	3362.07	18.76	20.53
22	9.00	76.14	82.49	649.06	7.39	189.20	74.38	5532.88	20.64	22.41
24	11.00	76.14	82.49	799.14	7.39	206.40	91.58	8387.51	22.61	24.38
SSX	17424.00					114.82				

Equations:

$$SSX = \sum_{i=1}^{n} (x_i - \bar{x})^2$$

$$A = \hat{\beta}_1^2 - \frac{\hat{\sigma}^2 t_{1-\alpha/2:n-2}^2}{SSX}$$

$$B = A(1 + \frac{1}{n}) + \frac{[y_0 - \bar{y}]^2}{SSX}$$

$$C = \hat{\beta}_1 [y_0 - \bar{y}]$$

$$D = t_{1-\alpha/2:n-2} \hat{\sigma}$$

$$L = \bar{x} + \frac{C - D\sqrt{B}}{A}$$

$$U = \bar{x} + \frac{C + D\sqrt{B}}{A}$$

APPENDIX C

DYNAMIC TORQUE DATA

Table 7. Dynamic Torque Data (90 RPM). Units in Microstrain.

Torque Setting 1	Torque Setting 2	Torque Setting 3	Torque Setting 4
99	147	196	244
99	149	199	243
99	148	200	243
99	148	198	245
100	150	200	241
97	146	201	249
101	150	198	245
96	150	198	242
100	148	196	243
100	149	199	243
97	153	197	245
98	149	200	246
102	149	197	240
100	147	201	245
100	149	199	244
99	150	201	245
100	150	200	243
99	152	195	243
99	150	198	245
97	149	199	245
99	147	200	243
97	150	201	243
98	150	199	244
98	154	199	242
97	153	198	243
97	154	196	242
101	150	204	243
98	148	199	243
102	151	197	243
99	151	199	244
97	151	198	243
99	149	198	247
100	149	197	248

	100	150	199	245
	100	150	201	245
	96	149	200	244
	102	154	201	247
	102	148	202	244
	98	150	201	244
	101	151	201	246
	102	151	201	244
	98	151	200	243
	101	153	200	244
	98	149	198	245
	99	149	201	243
	99	150	200	243
	100	151	201	245
	99	153	198	246
	103	149	201	244
	101	152	196	245
AVG	99	150	199	244
STD	1.70	1.88	1.84	1.66
N	50	50	50	50
MAX	103	154	204	249
MIN	96	146	195	240

Table 8. Data Collected from Dynamic Torque Trials. Units in Microstrain.

Trial 1			
Torque Setting 1	Torque Setting 2	Torque Setting 3	Torque Setting 4
100	150	197	244
97	147	197	242
99	147	198	243
99	150	197	244
98	152	199	244
97	152	199	242
99	156	201	248
101	152	200	247
98	153	199	245
101	151	198	244

Trial 2			
Torque Setting 1	Torque Setting 2	Torque Setting 3	Torque Setting 4
99	148	199	244
100	147	196	242
101	146	199	245
99	149	196	245
100	150	199	243
102	152	197	247
102	152	199	248
102	152	199	243
102	153	199	243
99	152	199	243

Trial 3			
Torque Setting 1	Torque Setting 2	Torque Setting 3	Torque Setting 4
97	153	197	244
98	149	198	242
102	149	197	245
101	151	196	245
103	148	197	242
101	150	197	243
99	151	199	246
100	152	196	246
101	153	201	245
97	151	199	244

Trial 4			
Torque Setting 1	Torque Setting 2	Torque Setting 3	Torque Setting 4
99	150	199	241
96	147	200	242
98	149	199	242
98	151	198	241
98	152	198	244
101	148	199	245
101	150	198	247
102	152	199	243
101	154	198	246
102	151	198	248

Trial 5			
Torque Setting 1	Torque Setting 2	Torque Setting 3	Torque Setting 4
101	149	202	245
97	147	199	245
98	146	199	243
99	147	203	245
100	148	198	244
99	150	199	248
100	151	197	244
99	153	199	246
102	151	197	240
99	149	201	244

Table 9. Single Factor ANOVA for Dynamic Torque Test Setting 1

Groups	Count	Sum	Average	Variance		
Sample 0	50	4962	99.24	2.88		
Sample 1	10	989	98.9	2.1		
Sample 2	10	1006	100.6	1.82222		
Sample 3	10	999	99.9	4.32222		
Sample 4	10	996	99.6	4.26667		
Sample 5	10	994	99.4	2.04444		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	20.72	5	4.144	1.43149	0.220138	2.31127
Within Groups	272.12	94	2.89489			
Total	292.84	99				

Table 10. Single Factor ANOVA for Dynamic Torque Test Setting 2

Groups	Count	Sum	Average	Variance		
Sample 0	50	7500	150	3.55102		
Sample 1	10	1510	151	7.333333		
Sample 2	10	1501	150.1	6.1		
Sample 3	10	1507	150.7	2.9		
Sample 4	10	1504	150.4	4.266667		
Sample 5	10	1491	149.1	4.766667		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	23.01	5	4.602	1.075287	0.379134	2.311268
Within Groups	402.3	94	4.279787			
Total	425.31	99				

Table 11. Single Factor ANOVA for Dynamic Torque Test Setting 3.

Groups	*Count*	*Sum*	*Average*	*Variance*		
Sample 0	50	9958	199.16	3.402449		
Sample 1	10	1985	198.5	1.833333		
Sample 2	10	1982	198.2	1.733333		
Sample 3	10	1977	197.7	2.455556		
Sample 4	10	1986	198.6	0.488889		
Sample 5	10	1994	199.4	4.044444		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	27.04	5	5.408	1.942351	0.094571	2.311268
Within Groups	261.72	94	2.784255			
Total	288.76	99				

Table 12. Single Factor ANOVA for Dynamic Torque Test Setting 4.

Groups	*Count*	*Sum*	*Average*	*Variance*		
Sample 0	50	12204	244.08	2.76898		
Sample 1	10	2443	244.3	3.788889		
Sample 2	10	2443	244.3	3.788889		
Sample 3	10	2442	244.2	2.177778		
Sample 4	10	2439	243.9	6.322222		
Sample 5	10	2444	244.4	4.266667		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.97	5	0.394	0.11618	0.988533	2.311268
Within Groups	318.78	94	3.391277			
Total	320.75	99				

Table 13. Linear Regression for Dynamic Torque Test Data.

Regression Statistics	
Multiple R	0.996
R Square	0.992
Adjusted R Sq.	0.987
Standard Err.	4.776
Observations	200

ANOVA					
	df	*SS*	*MS*	*F*	*Sig. F*
Regression	1	580344.224	580344.224	25442	4.39E-211
Residual	199	4539.331	22.811		
Total	200	584883.555			

	Coeff.	*Standard Err.*	*t Stat*	*P-val.*	*Lower 95%*	*Upper*	*Lower 95.0%*	*Upper*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	8.936	0.0166	536.760	0	8.9033	8.9690	8.9033	8.9690

Table 14. 95% Confidence Interval Calculation for Dynamic Torque at 90 RPM.

Setting						Strain			Lower	Upper
x	$[x_i-x]^2$	A	B	C	D	y	$[y_o-y]$	$[y_o-y]^2$	Limit	Limit
12	56.25	79.84	81.10	-653.77	9.36	100.00	-73.16	5352.39	10.26	12.37
12	56.25	79.84	81.17	-680.58	9.36	97.00	-76.16	5800.35	9.92	12.03
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.17	-680.58	9.36	97.00	-76.16	5800.35	9.92	12.03
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.10	-653.77	9.36	100.00	-73.16	5352.39	10.26	12.37
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.10	-653.77	9.36	100.00	-73.16	5352.39	10.26	12.37
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.17	-680.58	9.36	97.00	-76.16	5800.35	9.92	12.03
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48

12	56.25	79.84	81.03	-626.96	9.36	103.00	-70.16	4922.43	10.59	12.70
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.10	-653.77	9.36	100.00	-73.16	5352.39	10.26	12.37
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.17	-680.58	9.36	97.00	-76.16	5800.35	9.92	12.03
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.19	-689.51	9.36	96.00	-77.16	5953.67	9.81	11.92
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.07	-644.83	9.36	101.00	-72.16	5207.07	10.37	12.48
12	56.25	79.84	81.17	-680.58	9.36	97.00	-76.16	5800.35	9.92	12.03
12	56.25	79.84	81.14	-671.64	9.36	98.00	-75.16	5649.03	10.03	12.14
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.10	-653.77	9.36	100.00	-73.16	5352.39	10.26	12.37
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.10	-653.77	9.36	100.00	-73.16	5352.39	10.26	12.37
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
12	56.25	79.84	81.05	-635.90	9.36	102.00	-71.16	5063.75	10.48	12.59
12	56.25	79.84	81.12	-662.70	9.36	99.00	-74.16	5499.71	10.14	12.26
17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.35	-233.77	9.36	147.00	-26.16	684.35	15.52	17.62

17	6.25	79.84	80.35	-233.77	9.36	147.00	-26.16	684.35	15.52	17.62
17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.29	-153.34	9.36	156.00	-17.16	294.47	16.53	18.63
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.30	-180.15	9.36	153.00	-20.16	406.43	16.19	18.29
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.34	-224.83	9.36	148.00	-25.16	633.03	15.63	17.73
17	6.25	79.84	80.35	-233.77	9.36	147.00	-26.16	684.35	15.52	17.62
17	6.25	79.84	80.36	-242.71	9.36	146.00	-27.16	737.67	15.41	17.51
17	6.25	79.84	80.33	-215.90	9.36	149.00	-24.16	583.71	15.75	17.85
17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.30	-180.15	9.36	153.00	-20.16	406.43	16.19	18.29
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.30	-180.15	9.36	153.00	-20.16	406.43	16.19	18.29
17	6.25	79.84	80.33	-215.90	9.36	149.00	-24.16	583.71	15.75	17.85
17	6.25	79.84	80.33	-215.90	9.36	149.00	-24.16	583.71	15.75	17.85
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.34	-224.83	9.36	148.00	-25.16	633.03	15.63	17.73
17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.30	-180.15	9.36	153.00	-20.16	406.43	16.19	18.29
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07

17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.35	-233.77	9.36	147.00	-26.16	684.35	15.52	17.62
17	6.25	79.84	80.33	-215.90	9.36	149.00	-24.16	583.71	15.75	17.85
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.34	-224.83	9.36	148.00	-25.16	633.03	15.63	17.73
17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.31	-189.09	9.36	152.00	-21.16	447.75	16.08	18.18
17	6.25	79.84	80.30	-171.22	9.36	154.00	-19.16	367.11	16.30	18.41
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.33	-215.90	9.36	149.00	-24.16	583.71	15.75	17.85
17	6.25	79.84	80.35	-233.77	9.36	147.00	-26.16	684.35	15.52	17.62
17	6.25	79.84	80.36	-242.71	9.36	146.00	-27.16	737.67	15.41	17.51
17	6.25	79.84	80.35	-233.77	9.36	147.00	-26.16	684.35	15.52	17.62
17	6.25	79.84	80.34	-224.83	9.36	148.00	-25.16	633.03	15.63	17.73
17	6.25	79.84	80.33	-206.96	9.36	150.00	-23.16	536.39	15.86	17.96
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.30	-180.15	9.36	153.00	-20.16	406.43	16.19	18.29
17	6.25	79.84	80.32	-198.02	9.36	151.00	-22.16	491.07	15.97	18.07
17	6.25	79.84	80.33	-215.90	9.36	149.00	-24.16	583.71	15.75	17.85
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.36	248.78	9.36	201.00	27.84	775.07	21.56	23.67
22	6.25	79.84	80.35	239.85	9.36	200.00	26.84	720.39	21.45	23.56

22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.32	204.10	9.36	196.00	22.84	521.67	21.01	23.11
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.32	204.10	9.36	196.00	22.84	521.67	21.01	23.11
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.32	204.10	9.36	196.00	22.84	521.67	21.01	23.11
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.32	204.10	9.36	196.00	22.84	521.67	21.01	23.11
22	6.25	79.84	80.36	248.78	9.36	201.00	27.84	775.07	21.56	23.67
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	239.85	9.36	200.00	26.84	720.39	21.45	23.56
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44

22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.37	257.72	9.36	202.00	28.84	831.75	21.68	23.78
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.38	266.65	9.36	203.00	29.84	890.43	21.79	23.89
22	6.25	79.84	80.34	221.97	9.36	198.00	24.84	617.03	21.23	23.33
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.35	230.91	9.36	199.00	25.84	667.71	21.34	23.44
22	6.25	79.84	80.33	213.04	9.36	197.00	23.84	568.35	21.12	23.22
22	6.25	79.84	80.36	248.78	9.36	201.00	27.84	775.07	21.56	23.67
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	81.14	668.78	9.36	248.00	74.84	5601.03	26.82	28.93
27	56.25	79.84	81.11	659.84	9.36	247.00	73.84	5452.35	26.71	28.82
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60

27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.11	659.84	9.36	247.00	73.84	5452.35	26.71	28.82
27	56.25	79.84	81.14	668.78	9.36	248.00	74.84	5601.03	26.82	28.93
27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.09	650.91	9.36	246.00	72.84	5305.67	26.60	28.71
27	56.25	79.84	81.09	650.91	9.36	246.00	72.84	5305.67	26.60	28.71
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	80.98	606.23	9.36	241.00	67.84	4602.27	26.04	28.15
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	81.00	615.16	9.36	242.00	68.84	4738.95	26.15	28.26
27	56.25	79.84	80.98	606.23	9.36	241.00	67.84	4602.27	26.04	28.15
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.11	659.84	9.36	247.00	73.84	5452.35	26.71	28.82
27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.09	650.91	9.36	246.00	72.84	5305.67	26.60	28.71
27	56.25	79.84	81.14	668.78	9.36	248.00	74.84	5601.03	26.82	28.93
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60

27	56.25	79.84	81.02	624.10	9.36	243.00	69.84	4877.63	26.26	28.37
27	56.25	79.84	81.07	641.97	9.36	245.00	71.84	5160.99	26.49	28.60
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.14	668.78	9.36	248.00	74.84	5601.03	26.82	28.93
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
27	56.25	79.84	81.09	650.91	9.36	246.00	72.84	5305.67	26.60	28.71
27	56.25	79.84	80.95	597.29	9.36	240.00	66.84	4467.59	25.93	28.04
27	56.25	79.84	81.04	633.04	9.36	244.00	70.84	5018.31	26.37	28.48
SSX	6250					173.16				

Equations:

$$SSX = \sum_{i=1}^{n}(x_i - \bar{x})^2$$

$$C = \hat{\beta}_1[y_0 - \bar{y}]$$

$$L = \bar{x} + \frac{C - D\sqrt{B}}{A}$$

$$D = t_{1-\alpha/2:n-2}\hat{\sigma}$$

$$A = \hat{\beta}_1^2 - \frac{\hat{\sigma}^2 t_{1-\alpha/2:n-2}^2}{SSX}$$

$$U = \bar{x} + \frac{C + D\sqrt{B}}{A}$$

$$B = A(1 + \frac{1}{n}) + \frac{[y_0 - \bar{y}]^2}{SSX}$$

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