Measurement uncertainty analysis of dual wave ultrasonic fastener load estimation using the Micro-Control MC900 fastener transient system

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Abstract– This paper presents an analysis of the error generation mechanisms that affect the accuracy of measurements of MC900 fastener transient system. *The ultrasonic technology has been used for several years. The preload of the fastener is an area of interest and concern for the design engineers that are involved in the assembly of the diesel engine. The fastener load measurement by ultrasonic method has been widely used and has played an important role in applied mechanics department. Measurement errors and uncertainties frame a theory used more and more in the industrial domain, especially in the quality engineering department. The main reason underlying this is that there is a very big demand in characterizing the measurement results as complete and correct as possible*.

Key Words: uncertainties, measurement errors, MC900 system, non-destructive testing, ultrasound examination, procedure for calculation of measurement uncertainty

1. INTRODUCTION

In the first stage of the analysis, we show that number of sources of errors that might affect the measurement to highlight the contribution of each of them on the final result and on the total measurement uncertainty. The terms "error" and "uncertainty" should not be confused because, although they seem similar, they represent different concepts. Errors are those that affect the measurement, bringing changes to the final outcome, whereas uncertainty is the one that quantifies the accuracy with which the measurement result was determined. Knowledge of measurement errors and measurement uncertainties is of high importance because, according to them, a series of elements are established, like: the functionality of the pieces, their life span, and the evolution of the defect found in the pieces, and so on.

The combination of packaging cost & space constraints and increasing engine ratings pushes traditionally conservative designs closer to engineering and manufacturing limits. Exemplary of this are critical bolted joints, notably those connecting the cylinder block/head, main cap/block, connecting rod, and flywheel/damper pairs. One traditional limit is fastener yielding not confined to the thread/thread and under head contacts. Yielding poses both engineering and manufacturing problems, one of which is measuring fastener load. The traditional noninvasive method used in both communities is ultrasonic time of flight bolt gaging. Results measured using this method are affected by the length and acoustic velocity changes associated with yielding, biasing the load estimates reported by the instrument. The traditional approach to compensation for this bias is residual elongation correction [5] which adds a third measurement to the two typically required, then applies a previously obtained calibration to correct the loaded data for plasticity-induced effects. For small plasticity, a linear calibration captures the effect to a degree that doesn't affect the overall inaccuracy of the measurement. More recent applications take the fastener further into plasticity and require a quadratic correction.

2 Methodology for uncertainty measurement

The procedure provides general requirements and guidelines for expressing uncertainty results for ultrasonic nondestructive testing and recommends the general expression for the implementation and harmonization of requirements with the national and international standards, on the measurement uncertainty.

Ultrasound testing are non-destructive examination methods that use the sound waves to identify various types of defects that may be present in the structure of the materials and pieces taking into consideration. The MC900 hardware and MC911 software can determine the elongation of bolts under different loads.

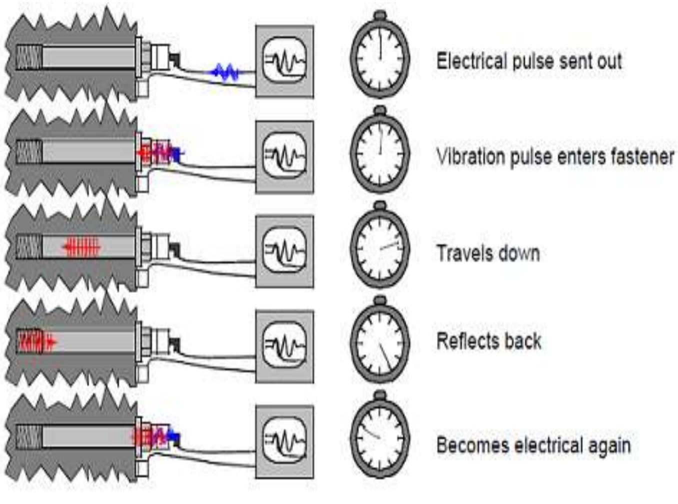
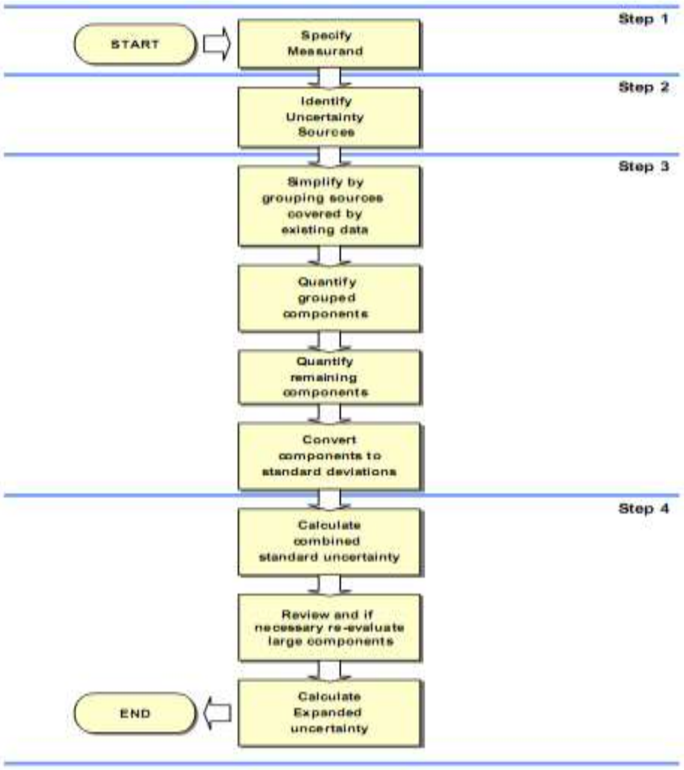


Figure 1 Ultrasonic time of flight

To calibrate the system, time of flight is used; an ultrasonic wave packet travels from one end of the fastener to the other and back. With this calibration elongations can be determined when bolts are under different types of load.

For evaluating and expressing the uncertainty of a result of a measurement several steps should be taken, as follows:



3. Calculating Standard uncertainties for associated each source:

STEP-1 Specify the measurement

Three values are directly measured by the instrument using an applied ultrasonic transducer pair:

Longitudinal mode- The longitudinal mode refers to a wave in which particles propagate in the same direction as the packet does, with all particles in the packet moving in the same direction.

Shear mode- Here atoms move in a single direction perpendicular to the propagating disturbance, something seen in nature when a tight cord (example: clothesline) is struck.

Temperature- at a point on the fastener head

To first order accuracy, the velocity of ultrasonic wave propagation depends only on the density and elastic modulus of the medium.

STEP-2 Cause and Effect diagram

All sources of errors which may affect the final result, contributing to the final measurement uncertainty should be expressed.

Measurement uncertainties are differentiated into two main categories:

- Type A Uncertainty: processed by statistical analysis of strings of observations (through direct measurements);
- Type B Uncertainty: taken from other sources (data sheets, specialty literature, etc.).

Three common models are:

- Rectangular
- Triangular
- Normal

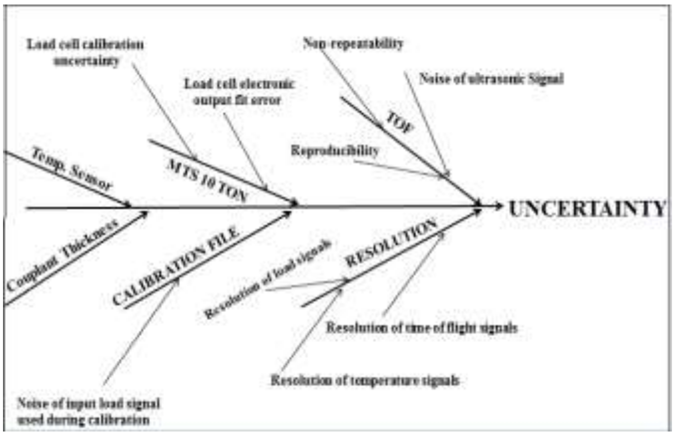


Figure 2: Cause and Effect Diagram

STEP-3 Calculation of the standard uncertainties associated with each identified sources of errors as well as the standard uncertainty associated with the sources of errors.

1. **Load cell calibration uncertainty-** The Tinius-Olsen load frame is calibrated annually to ASTM standard E-4, which requires capable calibration of each range within ±1% of reading on at least five points in each range.
2. **Load cell electronic output fit error-** A twelve-point linear fit was performed between the electronic output of the load frame (on its 24000 pound load range) and its electronic input digitized and rescaled in the MC900. The standard deviation of residuals to a linear fit is 8.55 lbf. A square distribution is again assumed.
3. **Noise of input load signal used during calibration-**Depending on the process of time of flight to load calibration, high frequency noise in the load input signal to the MC900 may impact results. This source was qualified by determining the standard deviation of the signal coming from the unloaded load frame at 10 samples per second, with the result at 9 lbf.

4. **Resolution of time of flight signals-**The resolution (not accuracy!) of time of flight signals is 0.1 nsec, not a significant impediment to load estimation.

5. **Resolution of load signals-**Discretization of load signals occurs in two places. Within the load frame, estimates are processed using a 12 bit DAC (4096 discrete levels). At the peak load calibrated for this test, this corresponds to 6 lbf.

6. **Resolution of temperature signals-**Temperatures are measured by the MC900 using a contact thermistor probe. The display resolution of temperature is 0.1 deg C.

7. **Noise of ultrasonic time of flight signals-** Six datasets were collected on the shear and longitudinal sensors of two different cap screws, with pairs of cap screws acquired simultaneously at 1000 samples per second. Three of these were collected with Bolt Temp temperature compensation on, three with no temperature compensation enabled. The root-mean square levels observed are described below.

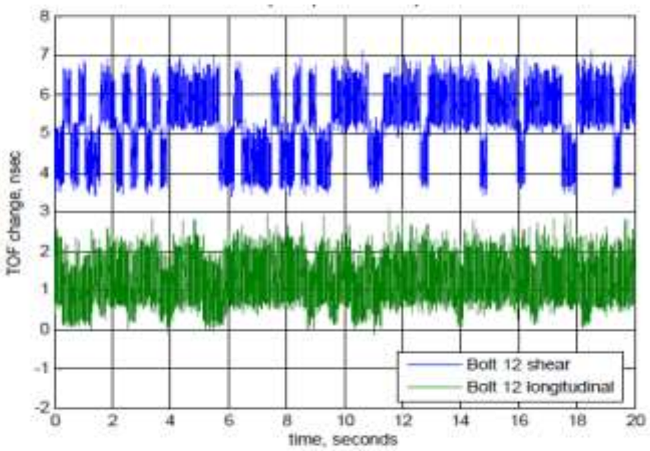


Figure 3 Time series/ noise 10 dataset (Capscrew 12 shear & longitudinal signals shown).

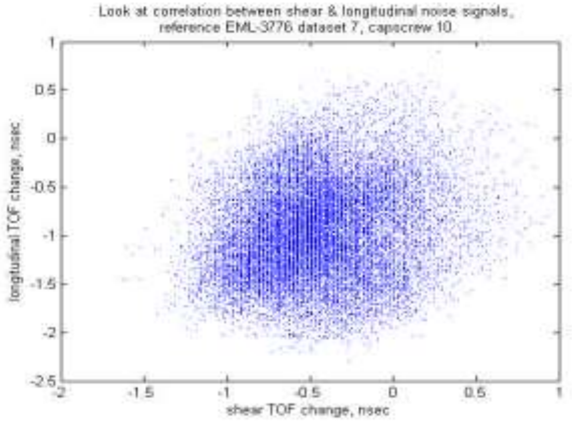


Figure 4 Scatterplot of shear and longitudinal times of flight showing the lack of temporal correlation.

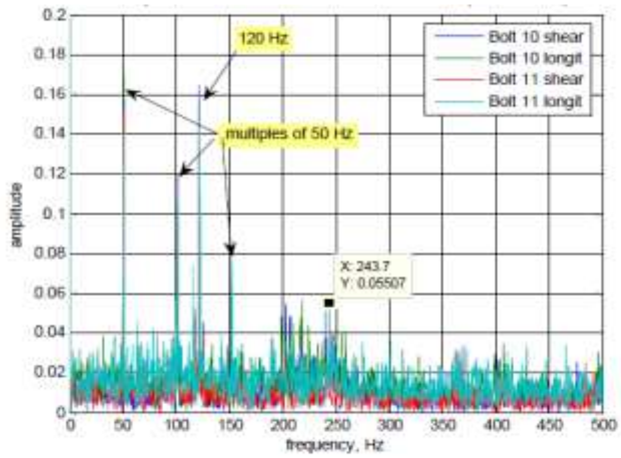


Figure5 Noise spectrum of caps crews 10 & 11 with BoltTemp temperature compensation on**.**

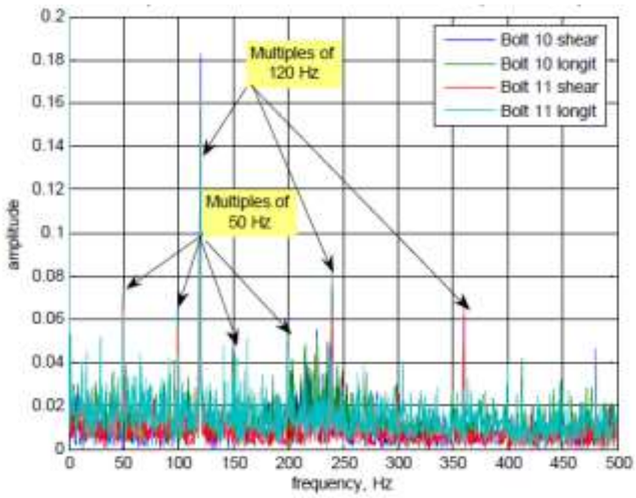
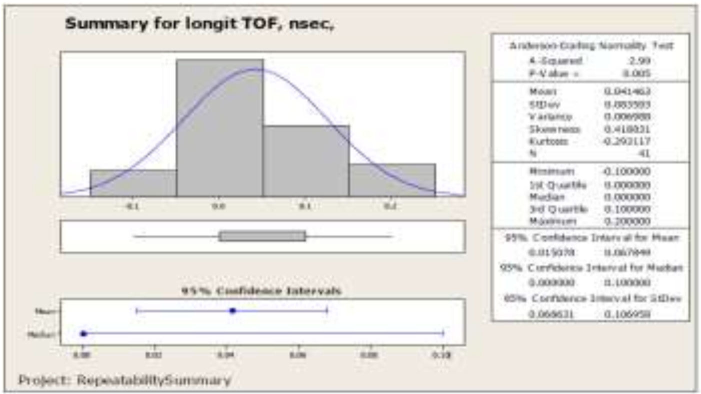
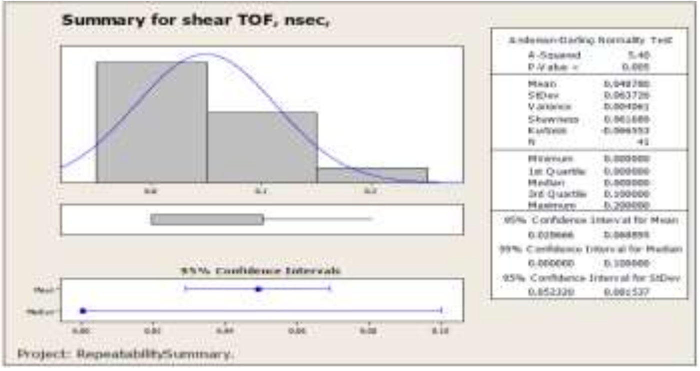


Figure 6 Noise spectrums of cap screws 10 & 11, temp compensation off.

8. **Non-repeatability of ultrasonic time of flight signals:** Measurement error is introduced because bolt gaging results are based on the results of pairs of measurements, thus pairs of couplings. Differences in coupling technique are manifested as an error, typically a pure variability where one person performs both couplings. My thinking was that introduction of an electrically coupled transducer like the Micro-Tensor III would reduce this source of variability and make the method easier for new or occasional operators.





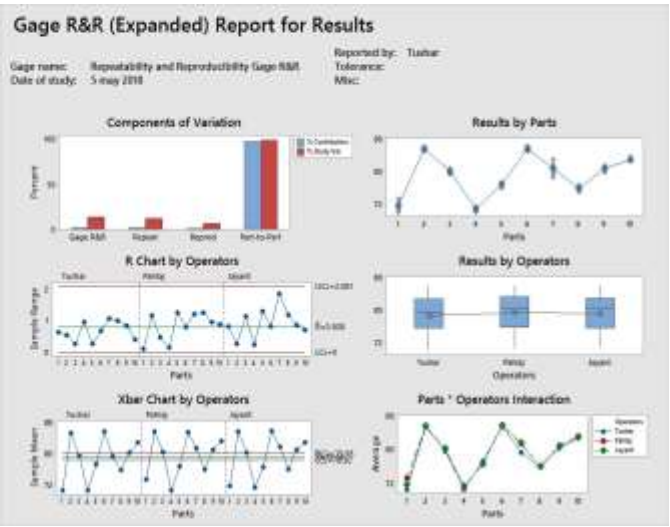


Figure 7 Gage R&R study for reproducibility and repeatability

9. **Error in thermal compensation-** As was stated in the introduction, typically-observed temperature changes induce sufficient time of flight variation to merit a separate transducer on commercially available bolt gages. The time of flight variation comes from a combination of acoustic velocity variation with temperature and thermal expansion (both are of the same arithmetic sign, therefore they are additive). In longitudinal time of flight measurement on common fastener steels, the former is responsible for approximately 90% of the overall variation.

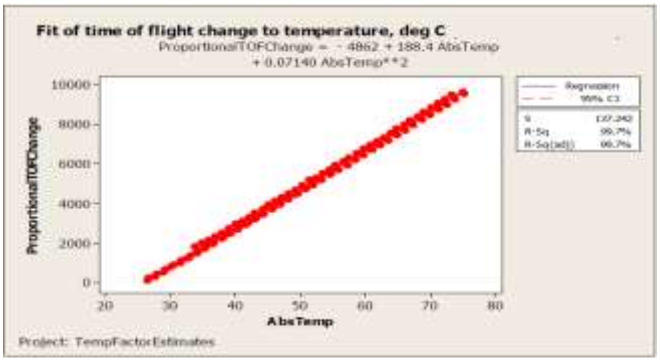


Figure 8 Effect of Temperature Compensation

Standard Uncertainty: Uncertainty components are evaluated by the appropriate method and each is expressed as a standard deviation and is referred to as a standard uncertainty.

Standard deviation (SD, also represented by the Greek letter sigma σ or the Latin letter s) is a measure that is used to quantify the amount of variation or dispersion of a set of data values.

Table NO 1 Standard uncertainty for each Error source:

Sr. NO	Source of Uncertainty	Standard Uncertainty
1	Noise on Time of Flight Signal	0.80 nsec
2	Load Cell Fit Error- Input to MC900	8.55 lbf
3	Calibration Fit Error	150 lbf
4	Longitudinal Non-Repeatability of TOF Measurement	0.08 nsec
5	Shear Non-Repeatability of TOF Measurement	0.06 nsec
6	instability During an Individual Measurement	0.15 nsec
7	Device Instability Between Measurement	0.00 nsec
8	Temperature Compensation Error(See TempComp Error)	161.52 lbf
9	Variability in Shear Compensation Factor	2.00 nsec
10	Uncompensated Decay of TOF Residuals	2.0 nsec

STEP-4 Determining the combined uncertainty for the result of the measurement and determining the expansion factor used to calculate the expanded uncertainty from the combined measurement uncertainty.

Combined Standard Uncertainty: Standard Uncertainty components are combined to produce an overall value of Uncertainty known as the Combined Standard Uncertainty.

It is estimated standard deviation equal to the positive square root of the sum of variances of all uncertainty components.

Expanded Uncertainty: It is defined as the interval within which lies the value of measurand.

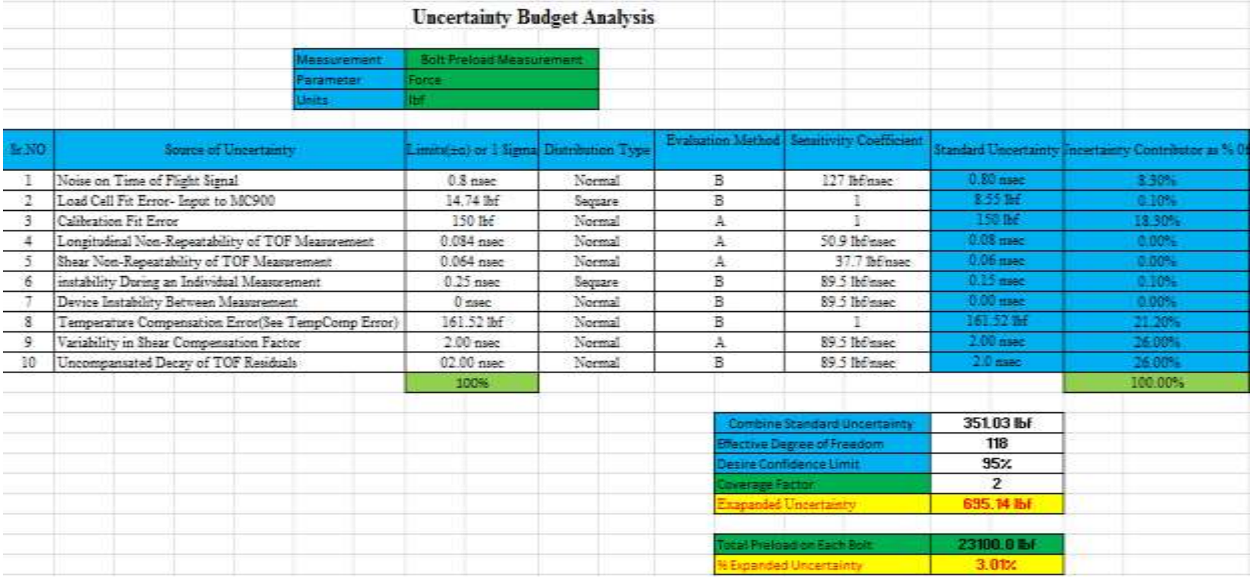
To calculate, multiply combined standard uncertainty with coverage factor (K)

$U = K \times U_C$

Coverage factor depends on level of confidence and degree of freedom.

K=2 for 95% of confidence

4. Uncertainty budget Analysis: An uncertainty budget is an itemized table of components that contribute to the uncertainty in measurement results. It reveals important information that identifies, quantifies, and characterizes each independent variable. Many of the significant contributors to uncertainty are not characteristic of the type of instrument used, so the previous analysis is a good introduction to this one.



Uncertainty Budget Analysis

Measurement	Bolt Preload Measurement
Parameter	Force
Units	lbf

Sr.NO	Source of Uncertainty	Limits(±σ) or 1 Sigma	Distribution Type	Evalsation Method	Sensitivity Coefficient	Standard Uncertainty	ncertainty Contributor as % Of
1	Noise on Time of Flight Signal	0.8 nsec	Normal	B	127 lbf/nsec	0.80 nsec	8.30%
2	Load Cell Fit Error- Input to MC900	14.74 lbf	Sequare	B	1	8.55 lbf	0.10%
3	Calibration Fit Error	150 lbf	Normal	A	1	150 lbf	18.30%
4	Longitudinal Non-Repeatability of TOF Measurement	0.084 nsec	Normal	A	50.9 lbf/nsec	0.08 nsec	0.00%
5	Shear Non-Repeatability of TOF Measurement	0.064 nsec	Normal	A	37.7 lbf/nsec	0.06 nsec	0.00%
6	instability During an Individual Measurement	0.25 nsec	Sequare	B	89.5 lbf/nsec	0.15 nsec	0.10%
7	Device Instability Between Measurement	0 nsec	Normal	B	89.5 lbf/nsec	0.00 nsec	0.00%
8	Temperature Compensation Error(See TempComp Error)	161.52 lbf	Normal	B	1	161.52 lbf	21.20%
9	Variability in Shear Compensation Factor	2.00 nsec	Normal	A	89.5 lbf/nsec	2.00 nsec	26.00%
10	Uncompansated Decay of TOF Residuals	02.00 nsec	Normal	B	89.5 lbf/nsec	2.0 nsec	26.00%
		100%					100.00%

Combine Standard Uncertainty	351.03 lbf
Effective Degree of Freedom	118
Desire Confidence Limit	95%
Coverage Factor	2
Exapanded Uncertainty	695.14 lbf

Total Preload on Each Bolt	23100.0 lbf
% Expanded Uncertainty	3.01%

5. CONCLUSION

Uncertainty is a parameter associated with the result of measurement that characterizes the dispersion of the values that could be reasonably attributed to measured value.

Three contributors dominate the overall measurement uncertainty of dual-wave load estimation: temperature compensation error, repeatable calibration fit errors and recovery (time-dependent relaxation of internal plastic strains generated during loading).

The internal temperature sensor in the MC900 ultrasonic pickup is very sensitive to operator-induced heating of its case and very insensitive to capscrew heating/cooling. It must be replaced for accurate readings. In addition, an error in the thermal compensation algorithm sometimes introduces noise in time of flight signals – this must be fixed.

The uncertainty of dual wave ultrasonic load estimates using the Micro-Control MC900 with Micro-Tensor III transducers and the algorithm described within is ± (600 lbf + 1.14% of reading) with 95% statistical confidence or better.

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