The use of permanent ultrasonic load transducers for real-time tightening and long-term fastener load monitoring studies

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Bolt Basics

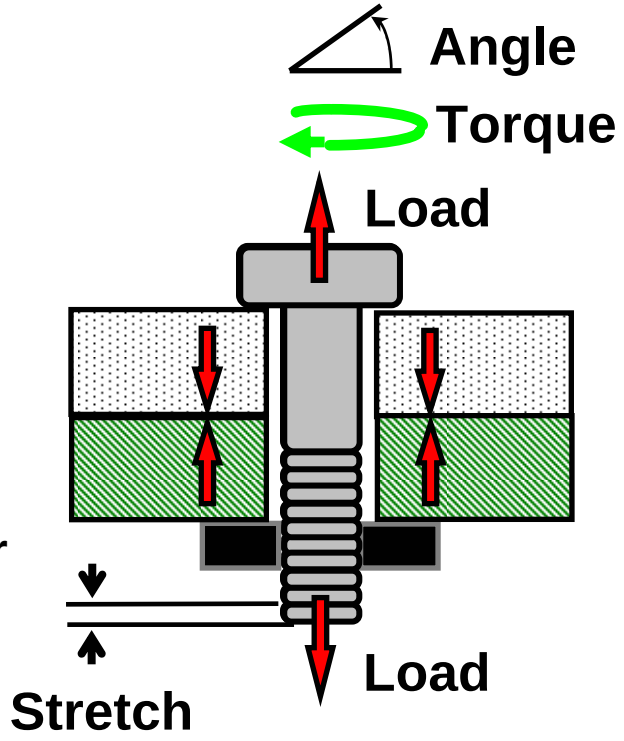
A bolt is a spring.

$\partial F \cong \partial \ell$

The elastic behavior of our bolting materials keeps everything together.

Stretch has been used for many years to control preload.

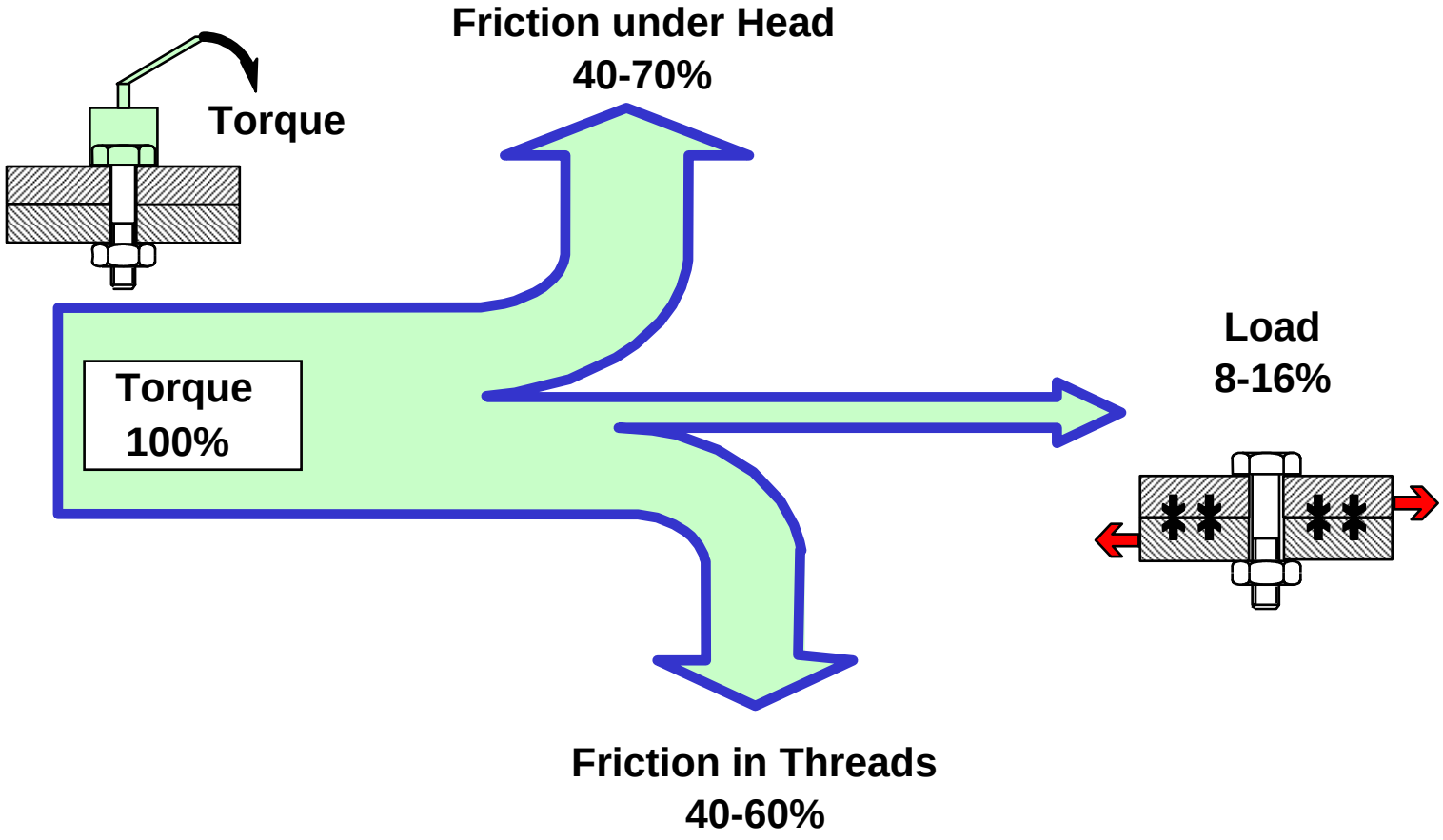
As long as the initial 'loading' of the fastener is below the yield point, the $\partial \ell$ from "zero load" to the target will be proportional to the tension force in the fastener.



If the fastener is taken beyond the yield point it is still the elastic "stretch" that produces the residual bolt load. An "unload" stretch measurement will produce an accurate load measurement in the fastener.

Bolt Basics

Torque, where does it go?



Bolt Basics

Bolt Tension Variation using Torque and Torque+Angle

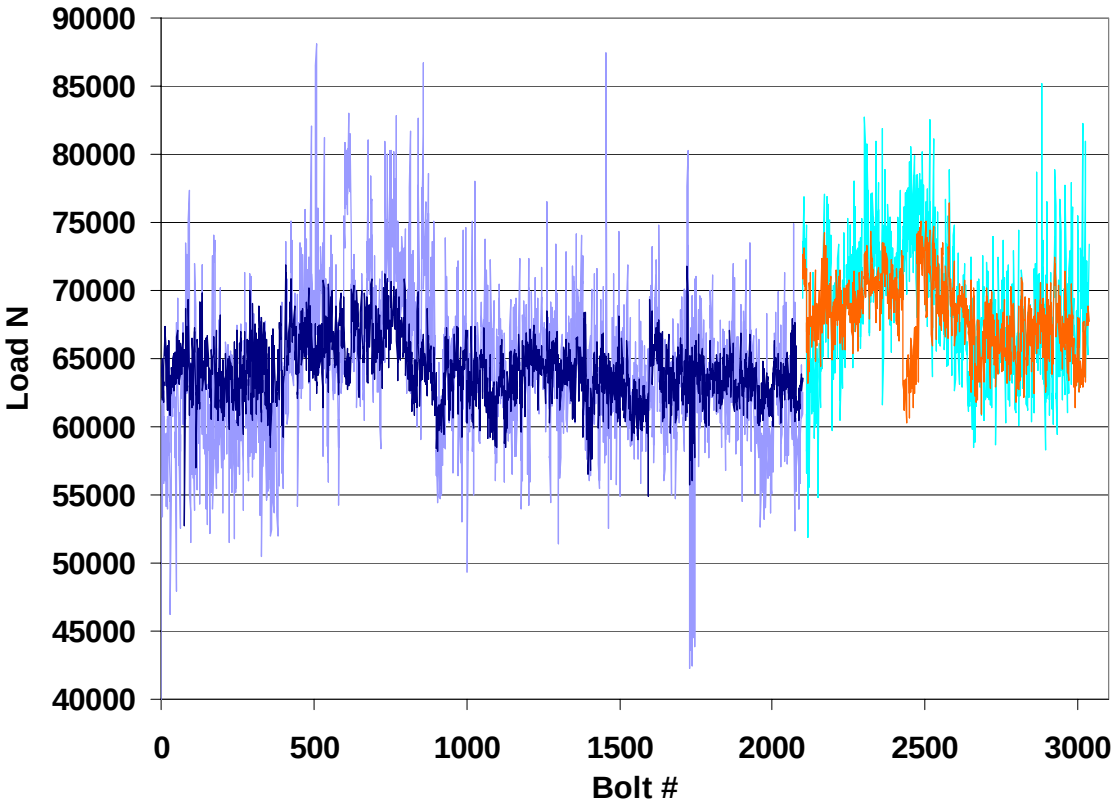
A large automotive manufacturer has a Torque+Angle tightening strategy QA requirement on each manufacturing lot of a M11 x 100 bolt, Class 10.9 head bolt.

- **Two manufacturers produce the fastener, the fastener test lab is within 10 miles of each plant.**
- **Three bolts from each lot are sent to the lab for testing, the bolts are fresh: no time dependent oil volatilization or settling**
- **Each bolt is tightened into a load cell with a torque-angle-controlled spindle**.
- **Over 1000 lots have been tested to date.**

Bolt Basics

Bolt Tension Variation using Torque and Torque+Angle

M11 x 100 - 10.9 head bolt.

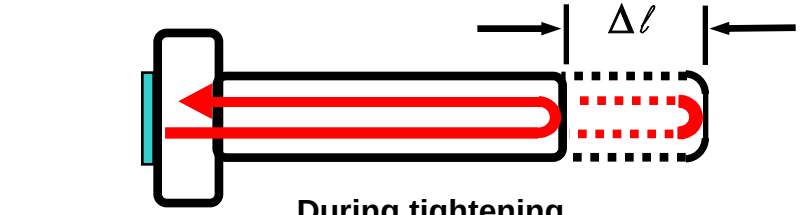


Load After Torque Only
Average Load: 65,672 N
3 sigma: +-17,215N
coeff var: 26.2%
manufacturer 1
manufacturer 2

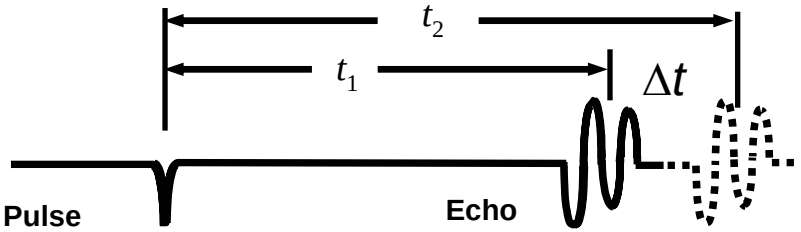
Load after Torque+Angle
Average Load: 65,330N
3 sigma: +- 9,239N
coeff. var: 14.1%
manufacturer 1
manufacturer 2

Ultrasound and Bolts

Ultrasonic wave pulse-echo ∂ time of flight measurement is analogous to stretch measurement for fastener load determination: single-ended micrometer

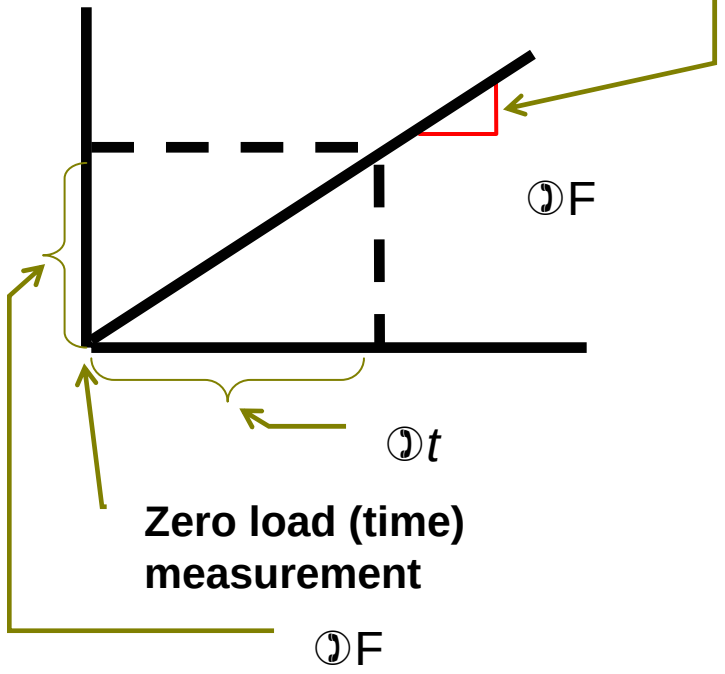


During tightening the fastener elongates with load



Loading the bolt creates stretch and lowers the velocity, increasing the time-of-flight

Slope: ∂F /∂t is ultrasonic stiffness of the "bolt spring"



Ultrasound and Bolts

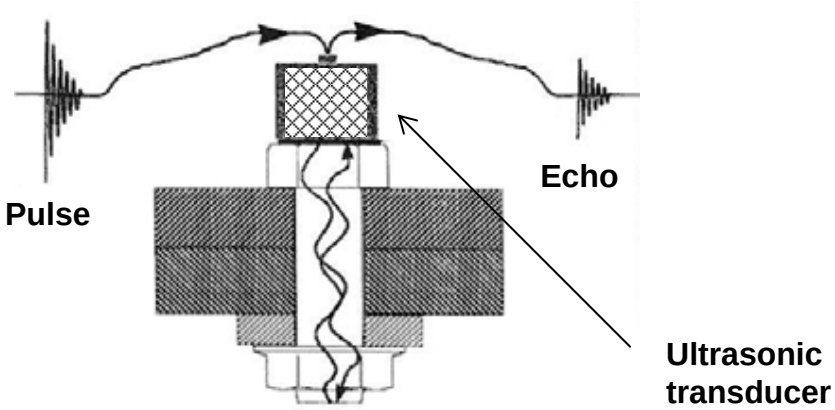
Pulse-echo ultrasonic measurement for bolt load determination: delta load/delta time.

In the bolt: ultrasound is ultrasound, force is force and delta time is delta time

Today, it is not a significant task to make hardware that has the required time measurement resolution: ~0.2ns.

Getting the ultrasound in and out of the fastener is the major issue.

Important: how the hardware "locks" on the proper (same) echo cycle every time (remove and replace) .



Typically a wave packet of 3-8 cycles at 2.5-15MHz (depending on manufacturer), every time a reading is taken is the significant issue.

- **Any questions: ask me.**

History

NASA developed ultrasonic bolt load measurement for the Space Shuttle Main Engines in the late '60s, using analog hardware with 0.1ns time resolution: Erdman hardware.

Screw-in transducers for good repeatability

Each bolt type is "acoustically ground" to the "same ultrasonic length"

Hand-held transducer boxes were first commercialized in the late '70s targeting "stretched" bolts: refineries, electric generating and other large bolts with lots of stretch.

- **need couplant to get ultrasound into bolt**

Glue-on transducers appear in early '80s

- **no couplant but large and not rugged**

Thin-film transducers move to aerospace, automotive test and development, 2001.

Technology

Reliable ultrasonic load readings using hand-held transducers are always an issue:

- **remove and replace technology is operator dependant**
  - **`remember single ended micrometer analogy**
- **training is most important!**

Bolt size is limited, smaller-stiffer the spring, the smaller the "stretch", the difficulty goes up.

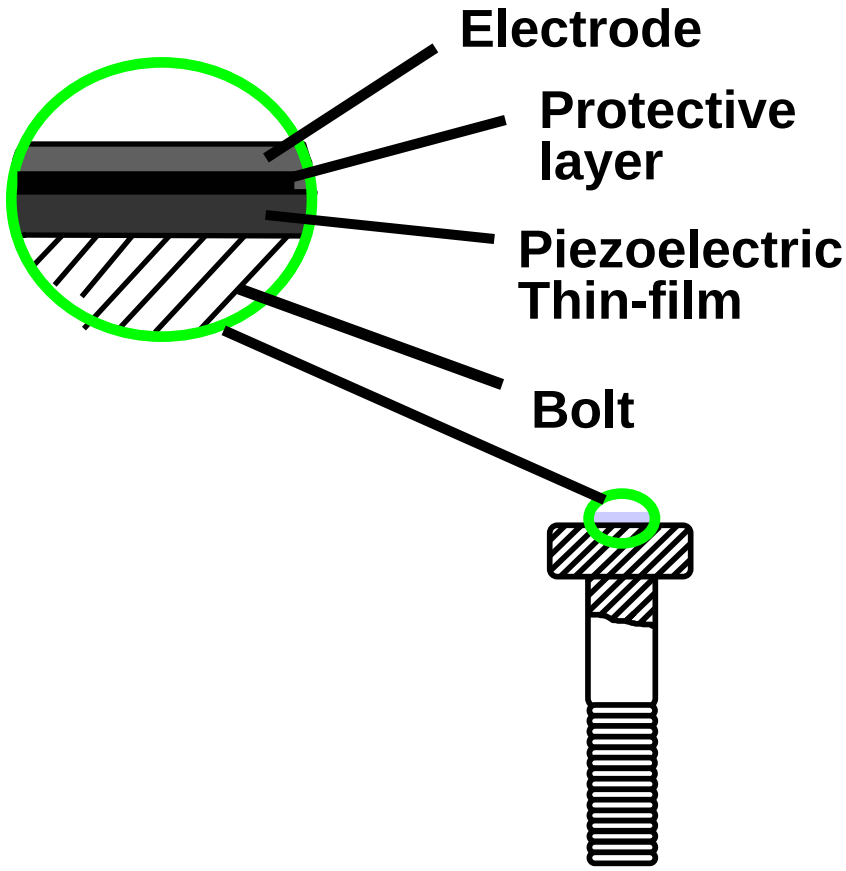
Replace operator with permanent transducers

Technology

Permanent solution: Make the transducer part of the bolt.

The Permanent Mounted Transducer (PMT)

Thin-film sputter deposition technology creates an ultrasonic transducer that is:



~24μm thick, very low profile
low mass, dynamic
layers are ceramic and metal
rugged, high temperature
no bonding agent

Technology

The Permanently Mounted Transducer

Sputtered Fastener Coating

- **Your fastener**
- **Coated with piezoelectric thin-film**
- **Proven low temperature vacuum process**

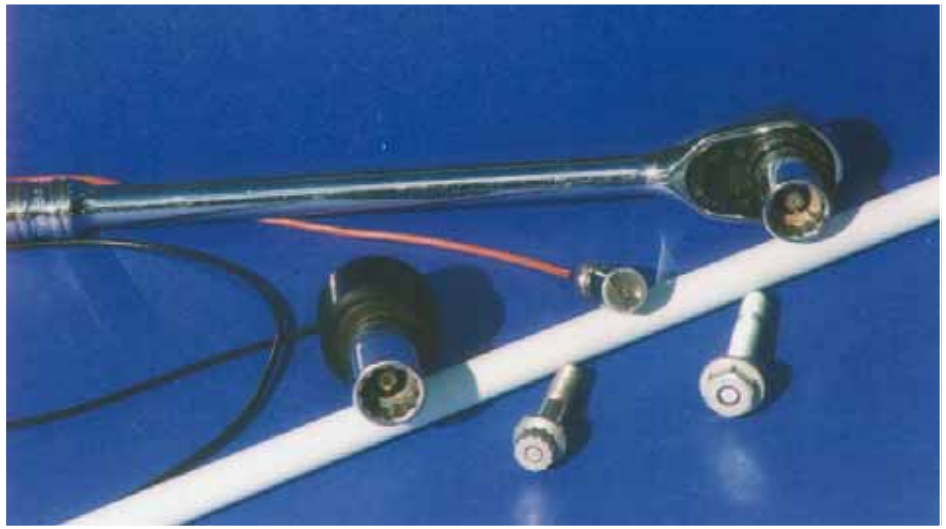
PMT: in the field

Reading the the Permanent Mounted Transducer (PMT)

- **Only a touch: no coupling gel, no operator Remove & Replace variance**

Hand tools

- **non-magnetic probe: just change the std. socket**
- **magnetic probe: small and simple**
- **hand wrench: manual real-time load control**



PMT: in the field

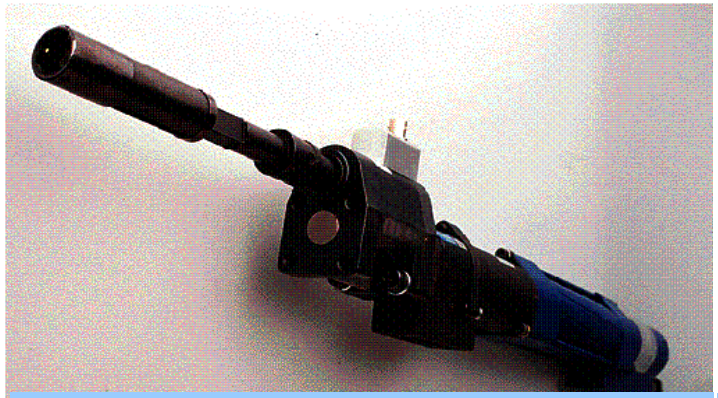
Dynamic readings possible:

Slip rings

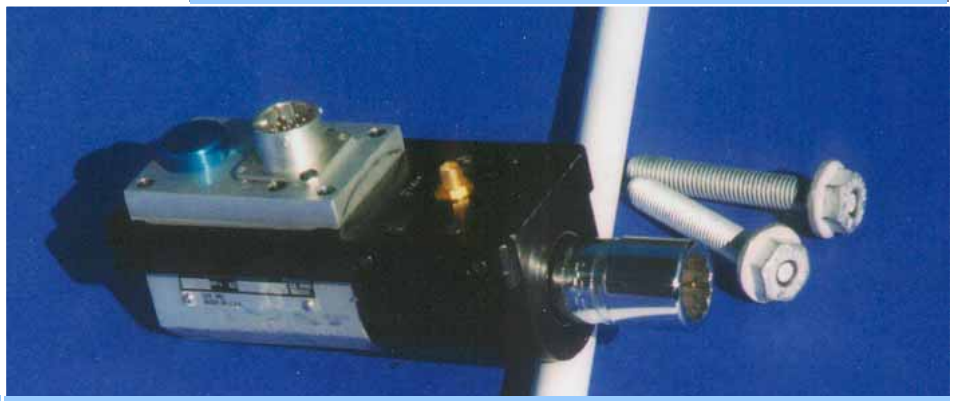
Right angle nut runners

In-line production tools

Right-angle nut runner



In-line spindle

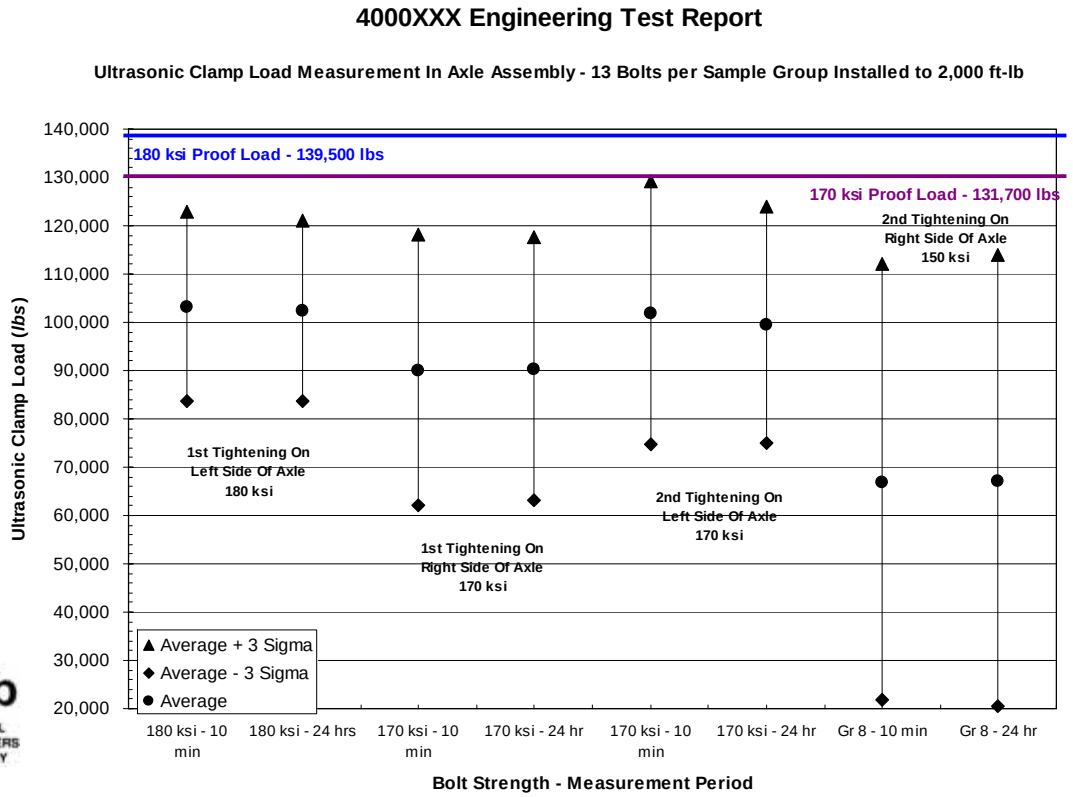


In-line slip ring with torque-angle transducer

PMT in the field: relaxation

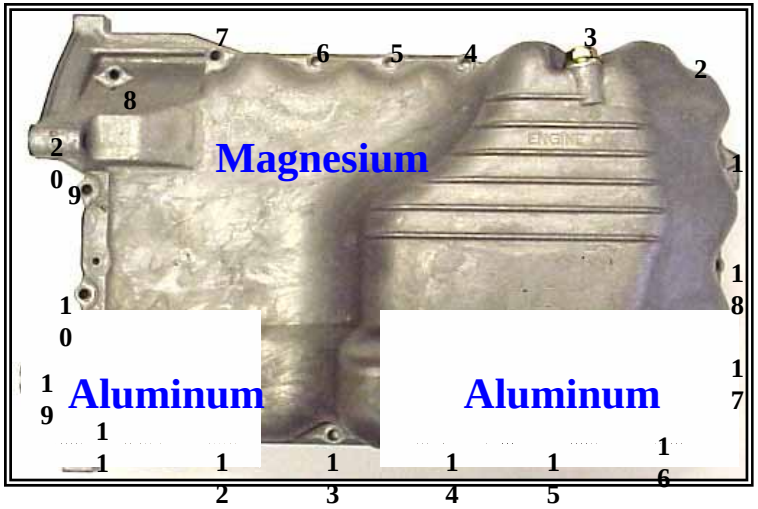
Problem: manufacturer of large off-road vehicles uses 180ksi bolt for axle flange: bolts break. Bolt supplier wants to solve problem with lower strength bolt. What happens on the production floor?

Solution: 50 each - 1.25” axle flange bolts, 4 strength grades, tightened to 2000 ft-lbs. Data taken after assembly and after 24 hrs.



PMT in the field: relaxation

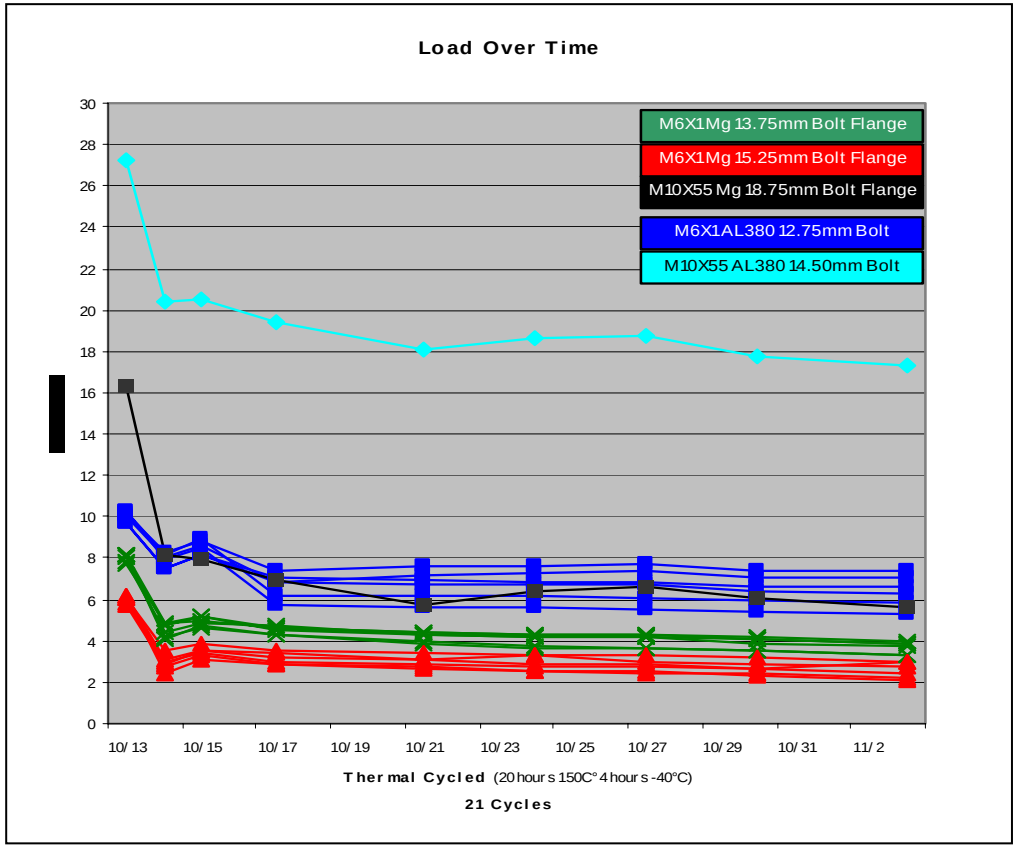
Problem: customer of casting supplier wants to move to a magnesium oil pan cover. Can the magnesium cover be substituted for the aluminum with no long term load/temp relaxation problems?



Different bolt geometry's are PMT coated, assembled in aluminum and magnesium test articles and thermally cycled (20 hours 150C° 4 hours -40°C) for 21 days.

PMT in the field: relaxation

Solution: Magnesium exhibits initial lower loads but relaxation is flat.



PMT in the field

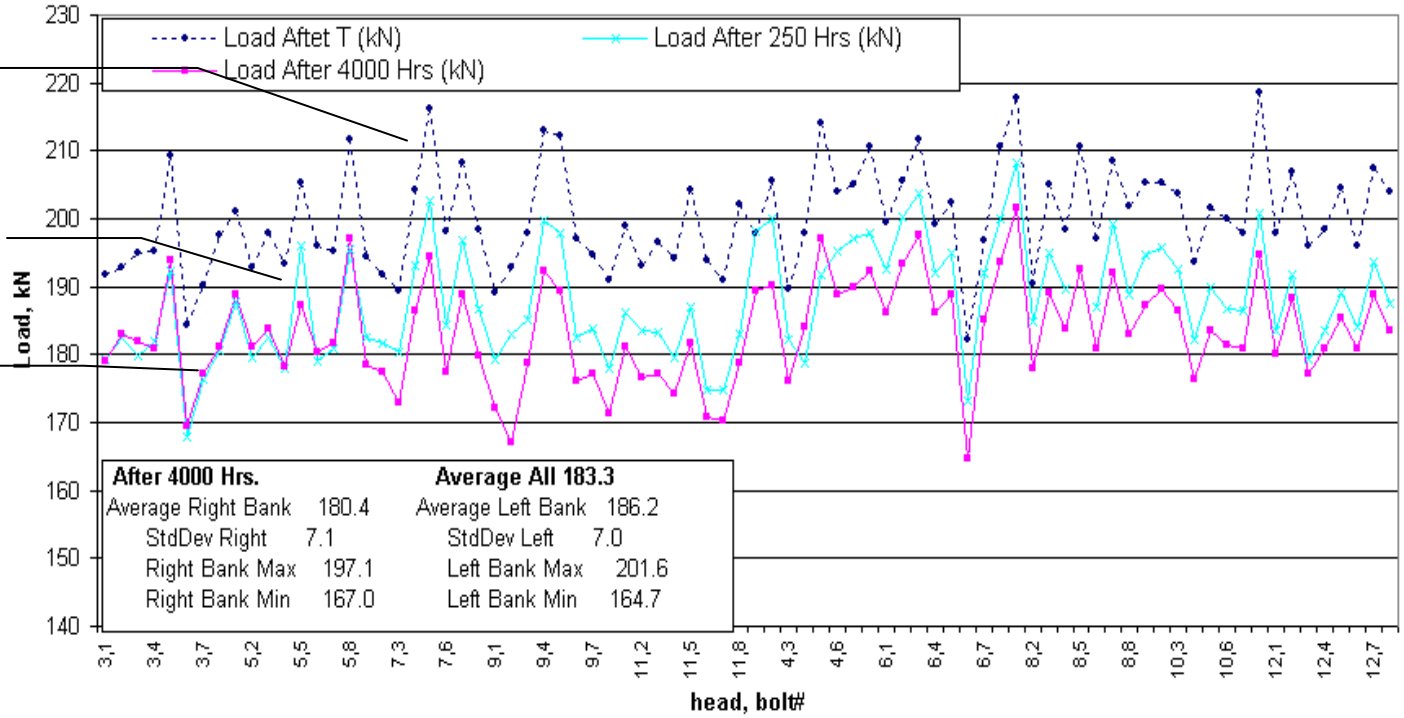
Large diesel engine maker wants to study gasket loads of field rebuild procedures, in the field (makes sense). 3/4x10” head bolts.
10 heads - 8 bolts per head

PMT in the field: relaxation

Field torque-angle assembly procedure

Head bolt load after 250 hrs

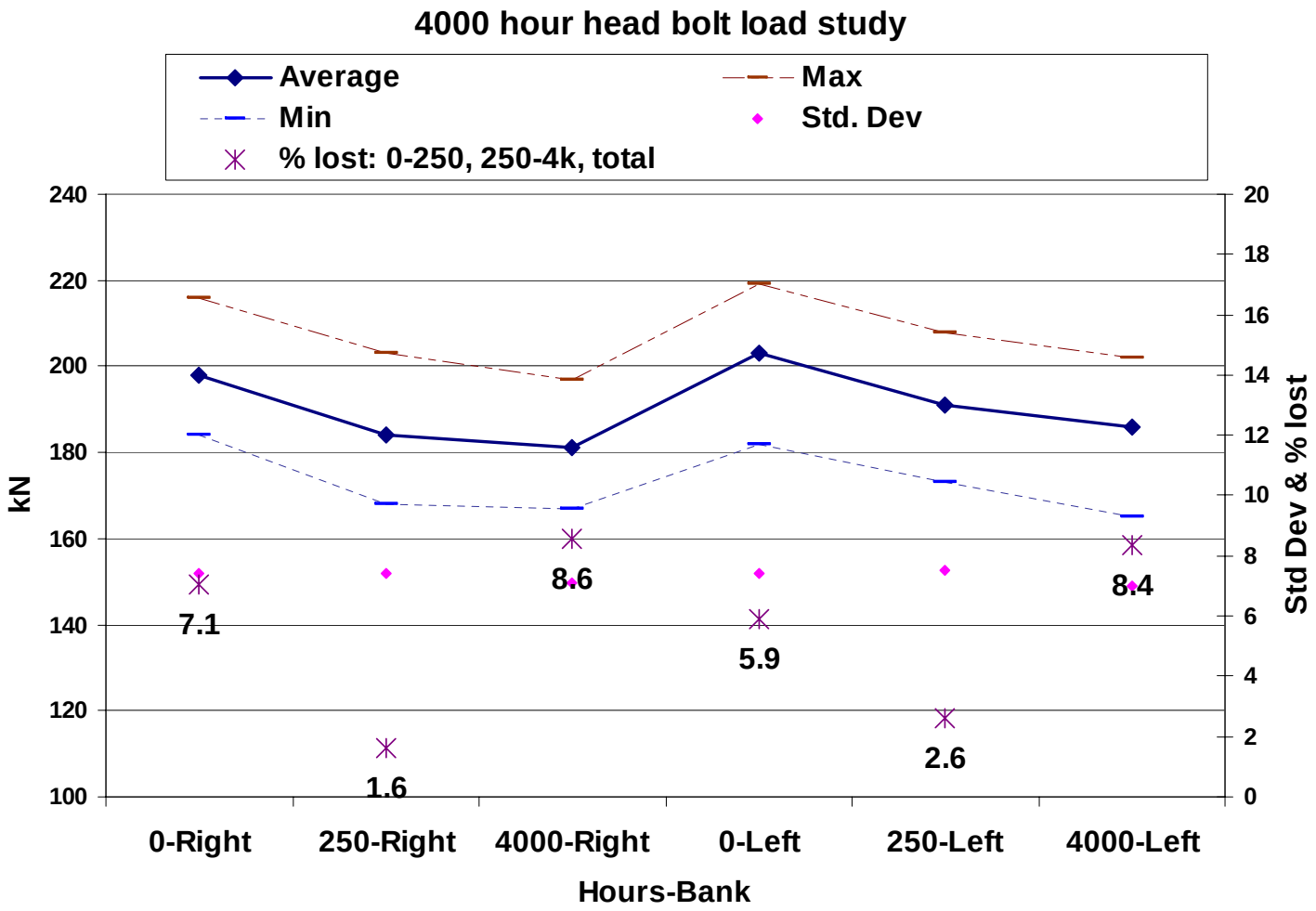
Head bolt load after 4000 hrs



After Torque	Average All 200.1		
Average Right Bank	197.8	Average Left Bank	202.5
StdDev Right	7.4	StdDev Left	7.4
Right Bank Max	216.1	Left Bank Max	218.5
Right Bank Min	184.3	Left Bank Min	182.3

After 250 Hrs.	Average All 187.8		
Average Right Bank	184.2	Average Left Bank	191.4
StdDev Right	7.4	StdDev Left	7.5
Right Bank Max	202.5	Left Bank Max	208.3
Right Bank Min	167.8	Left Bank Min	173.2

PMT in the field: relaxation



PMT in the field: relaxation

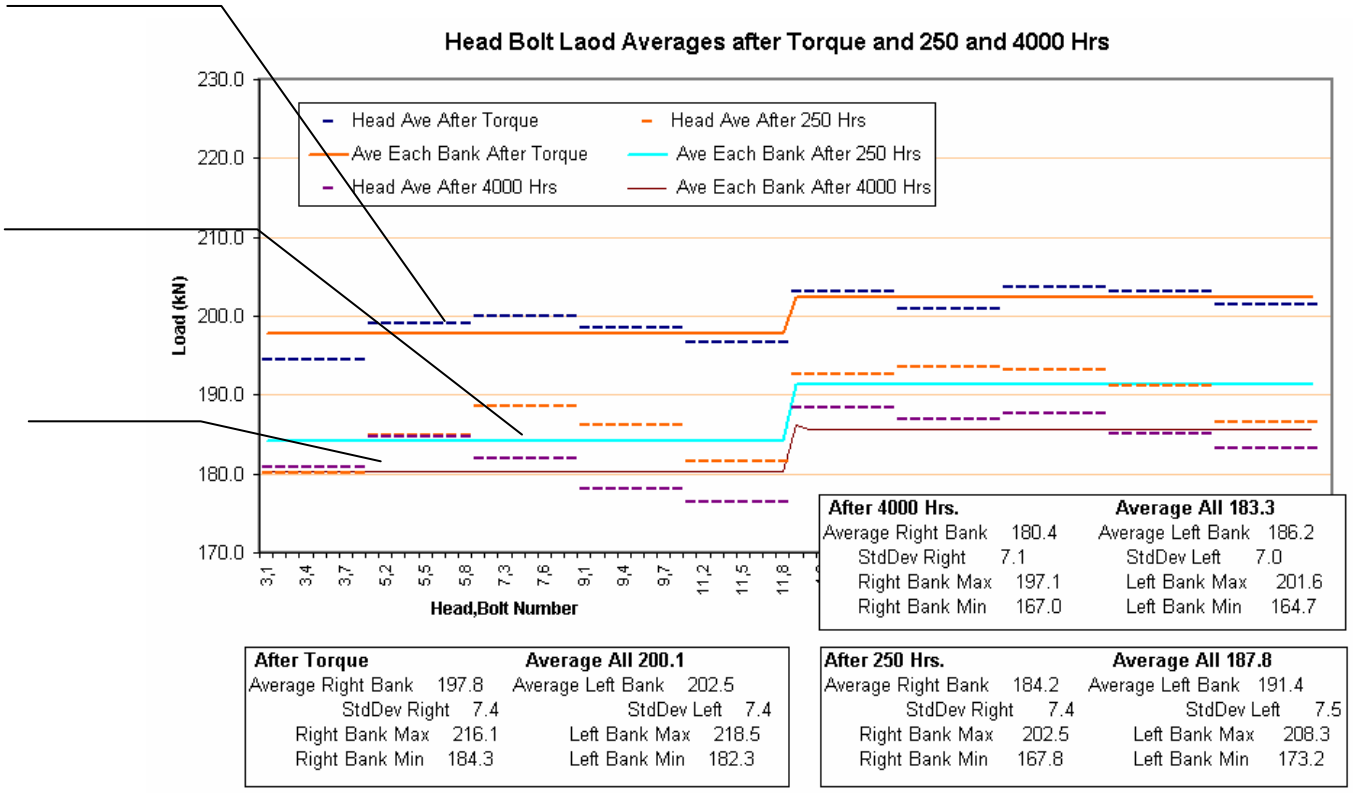
Solution: 4000 hours of field operation with PMTs

no couplant, no magnets, no problems.

Field torque-angle assembly procedure, average of each head group

Average head bolt load after 250 hrs

Average head bolt load after 4000 hrs



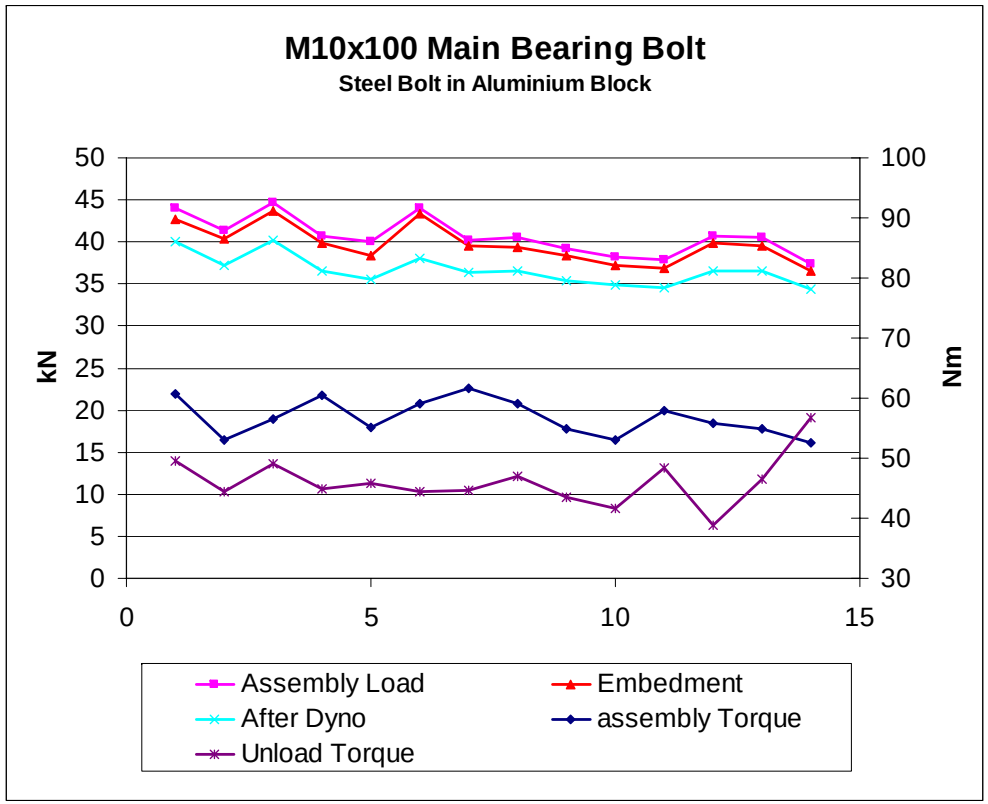
PMT in the field: relaxation

Main Bearing cap bolt assembly load study

Procedure: snug torque + fixed angle to elastic target

Data collected:

- Assembly load
- Assembly torque
- Embedment load
- Load after dyno
- Break-away torque after dyno

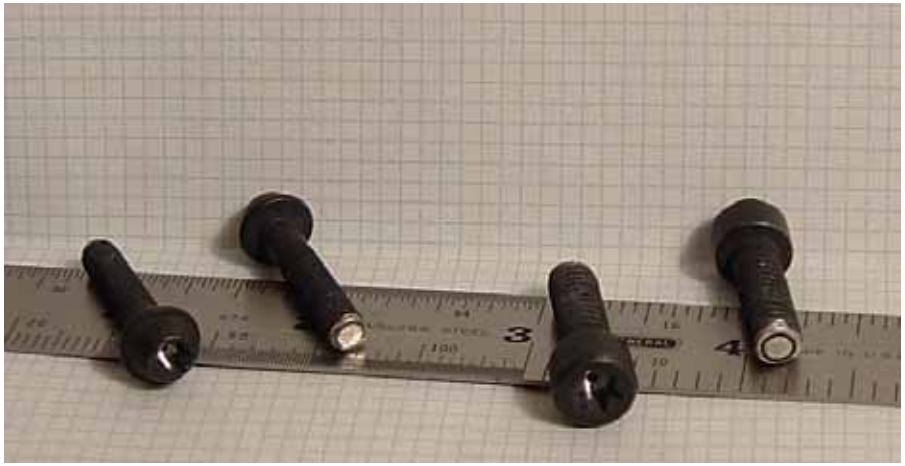


PMT in the field: relaxation

2000 Hours:

at 300°F for gasket relaxation tests

Same bolts are in for another 2000 hours!



PMT in the field: relaxation

2+ Years:

-70 to +180 - 24-7

Invaluable relaxation data

Survived +180 to -300 shock test!

PMT in production

Will PMTs perform under production conditions?

A twin spindle inline tool was built to monitor the elastic torque-angle process of 17,000 M10x100 Torx head main bearing cap bolts.

Bolts were PMT coated and uni-moly coated (barrel). Assembled once in line-boring operation, and then assembled in unit.

Operation was semi-manual and low volume: 50 engines/week.

PMT control box

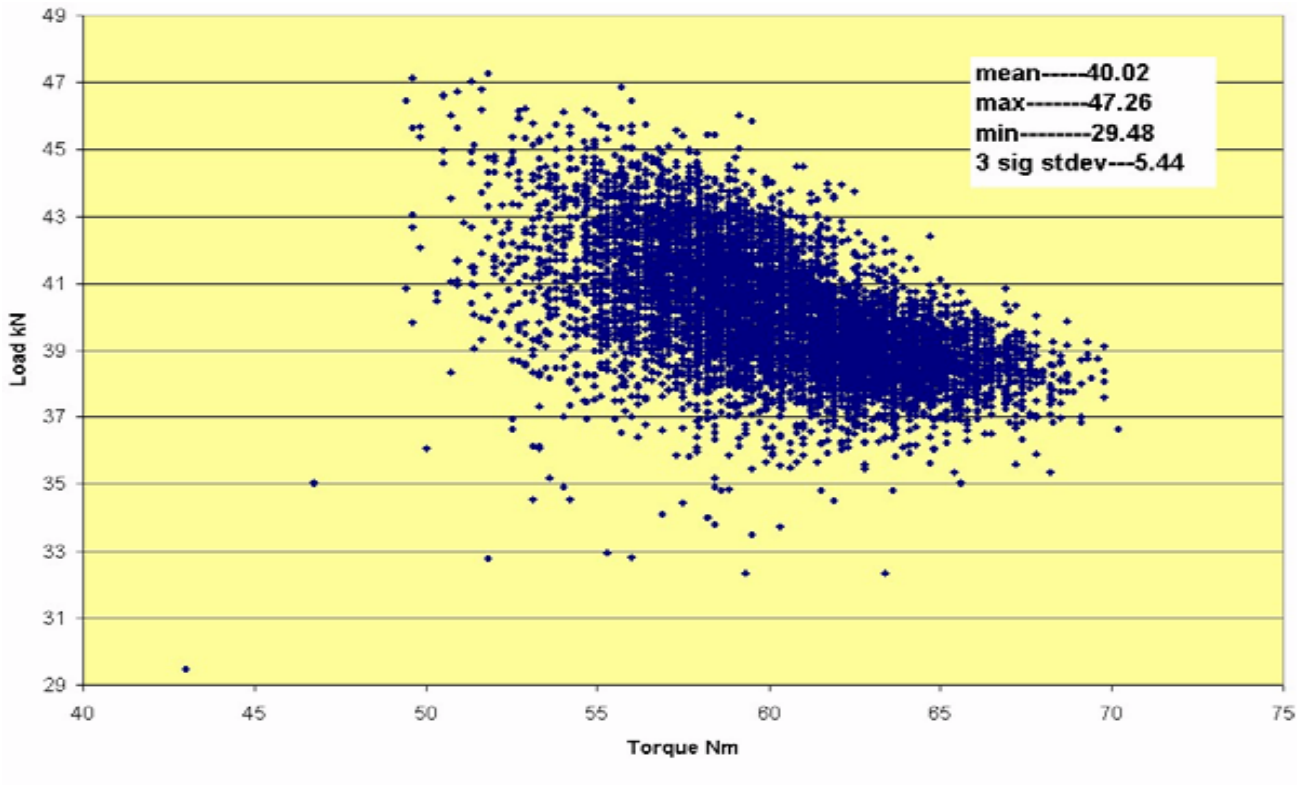
Main bearing caps

Production tool

PMT in production

Results: Production Data

17,000 10.9 M10x110 steel bolts into Al, Unimoly paste coating snug + angle, recorded final ultrasonic load, angle and torque at wrench shut-off. Test did not affect operator or process at all!

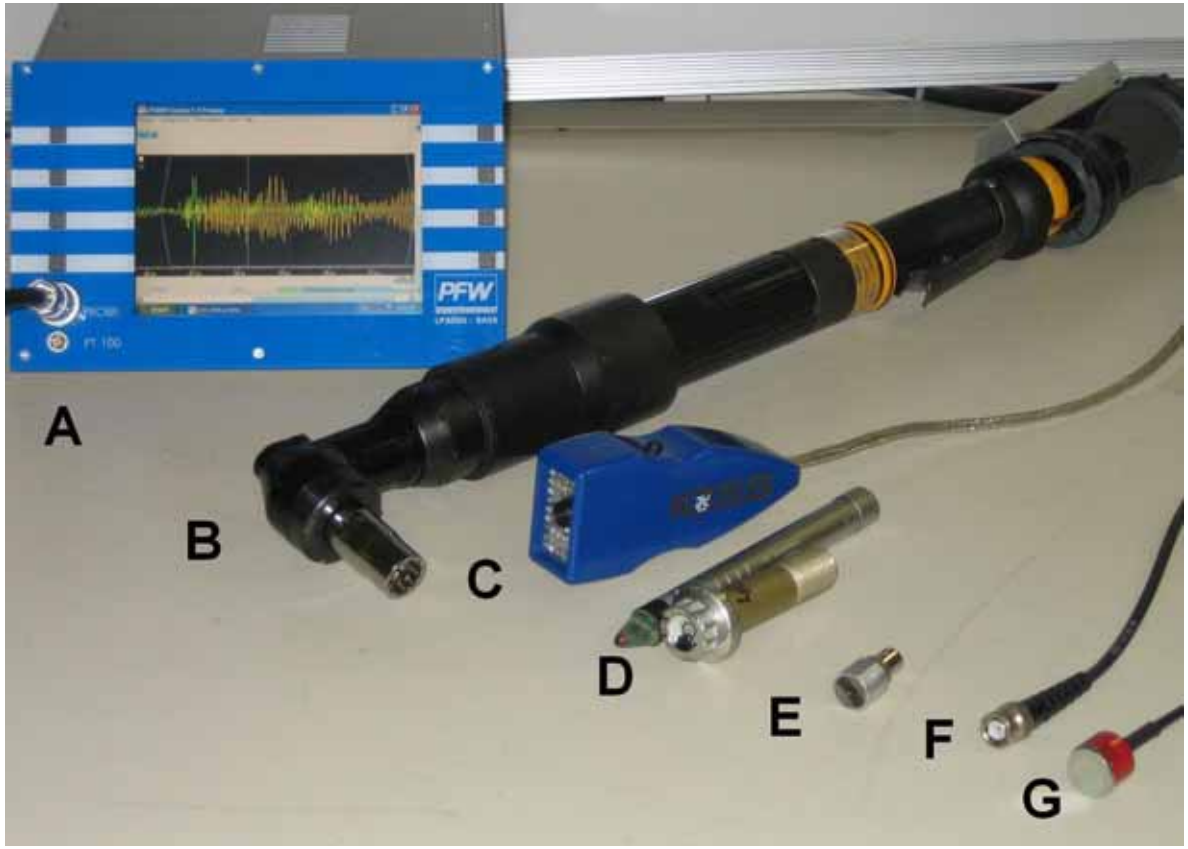


Field Tools

Handheld portable laboratory and field device

- **LoadProbe 3000B**
- **Battery powered**
- **Internal data storage**
- **Windows OS**

PMT: Hardware



A. LoadProbe 3000 Compact
B. Rt angle tool
C. Dot Matrix ID reader
D. ID'd Bolt
E. Magnetic Probe
F. Cable
G. Temperature Probe

PMT system

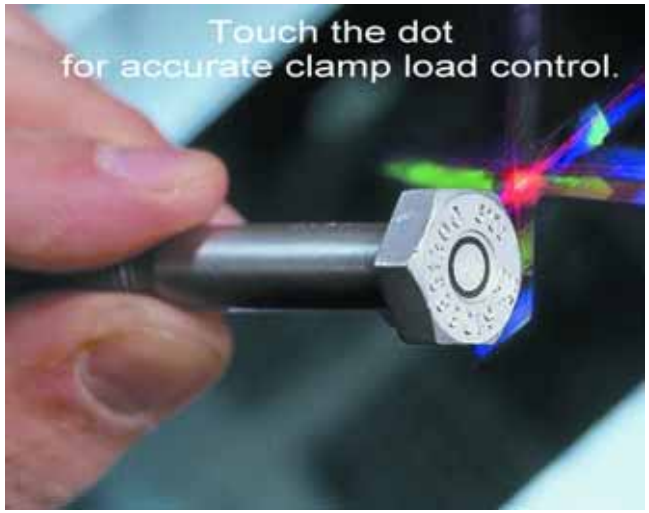
State of the art technology for fastener clamp load measurement

Rugged

- **Achieve design clamp loads at assembly - any time**
- **The PMT is part of the bolt**
  - **no magnets, no glue**
- **Thin-film piezeo-crystal and metal electrode**
  - **total 25μm ZnO and metal (Ni-Cr or Sn)**
  - **high temperature operation**
  - **Low mass for dynamic loading**
- **Document quality to assure safety**

Precise

- **The only operator independent system**
- **Field use.**
- **No coupling fluid variance**
- **No remove/replace placement error**
- **Touch and read that's it!**



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