



TRAXX



# ULTRASONIC TENSION MEASUREMENT

The principle of the method explained to the uninitiated and re-explained to the experienced

# I Measuring principle

The measuring principle is very simple. It consists in measuring the elongation of the screw or stud as a result of the tension produced by tightening. As this elongation is proportional to the tension (let's assume for now that we are remaining within the sphere of elasticity), the tension can be deduced from it simply by applying a coefficient.

The ultrasonic transducer placed on the head of the screw or stud acts:

- Firstly as an emitter that converts the electric pulse supplied by the measuring system into an ultrasonic wave that will propagate longitudinally in the material.
- Then as a receiver that will receive the greatly weakened ultrasonic wave reflected off the bottom of the screw, and convert it into an electric signal that will be processed by the measuring system.

This operation is repeated several hundreds or thousands of times per second. Each time a pulse is «fired», the measuring system measures the time for the echo to return after the pulse is emitted.

This is the principle of sonar, but the high propagation velocity of ultrasonic waves (approximately 5,800 m.s<sup>-1</sup> in steel) and the required resolution of the elongation measurement (a few  $\mu\text{m}$ ) requires a time measurement resolution in the order of one nanosecond (10<sup>-9</sup> s).

The time measured by the system is known as the “ultrasonic length”.

As we will see, we do not need accurate knowledge of the ultrasonic wave propagation velocity in the material.

At rest, in the so-called INITIAL state, an ultrasonic length  $L_i$  is measured.

After tightening, in the so-called FINAL state, an ultrasonic length  $L_f$  will be measured.

This ultrasonic elongation  $L_f - L_i$  can be attributed to:

- The mechanical elongation of the screw
- The decrease in the propagation velocity of the ultrasonic wave due to the tension introduced in the material.

Generally, the effect due to the velocity is largely predominant, to a greater or lesser extent depending on the material. The system cannot distinguish between the two causes. However, various research projects, including those at CETIM (the French Industrial and Mechanical Technical Centre), have shown for a long time (forty years) that as these two effects are proportional to the tension, so is a combination of them. And luckily so, because it's what makes the method applicable!

The proportionality ratio between the ultrasonic elongation (the quantity measured) and the tension produced (the quantity we want to find out) will be determined by **PRIOR CALIBRATION** of the assembly.

For this, a mock-up representative of the assembly (same type of screw/stud and same tightened length) is subjected to calibrated stresses, for example on a tensile testing machine.

For each tension value, measured by the tensile testing machine or by a force sensor, the measuring system records the corresponding ultrasonic elongation.

The system then calculates and records the proportionality coefficient K.

$$\text{Tension (daN)} = K \times \text{Ultrasonic elongation (ns)}$$

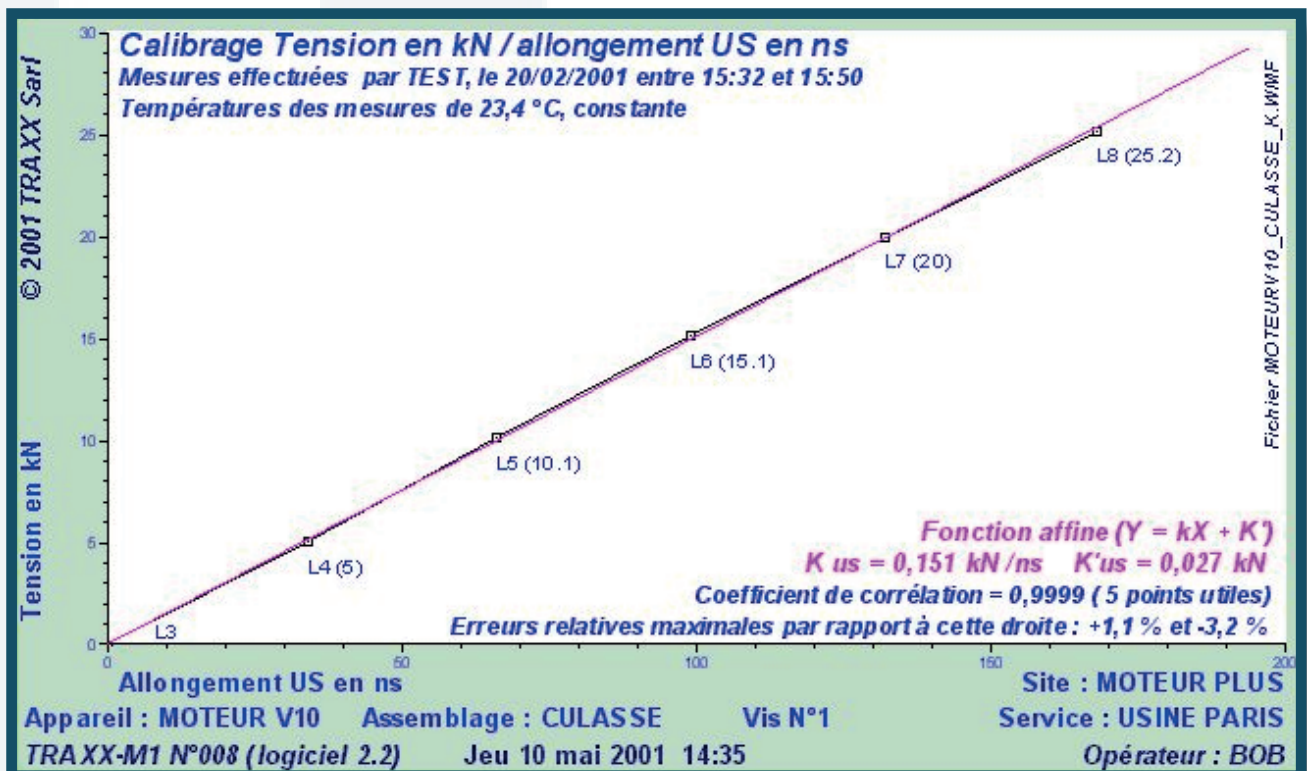
K is expressed in daN.ns-1 or kN.ns-1

This method automatically takes into account the ultrasonic wave propagation velocity and the changes made to it by the tension, without it being necessary to know them. This operation takes only a few minutes. It is only carried out once for a given type of assembly.

## Example of actual calibration

The x-axis shows the ultrasonic elongation in nanoseconds measured by the system. The y-axis shows the tension in kiloNewtons measured by the tensile testing machine. The calculations and graph are produced automatically by the Traxx-M2 measuring system.

Here, the near-perfect linearity gives a K of 0.151 kN per ns.



The coefficient K' has been added by the system to take account of the fact that the calibration line does not pass through the origin (due to the positioning of the assembly at the start of tensioning).

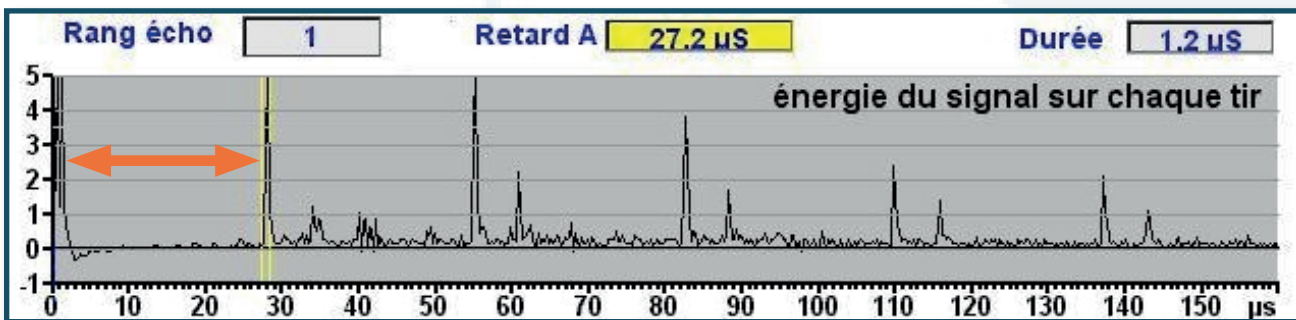
Remarque :

This calibration allows for the elongation of the screw to be linked to the tension to be measured. Screws from the same batch can therefore vary slightly in size without causing any problems; they don't all need to be ground to the nearest  $\mu\text{m}$ ! An initial length measurement will be taken on each screw in the series. The system will use the difference (final length - initial length) to calculate the tension.

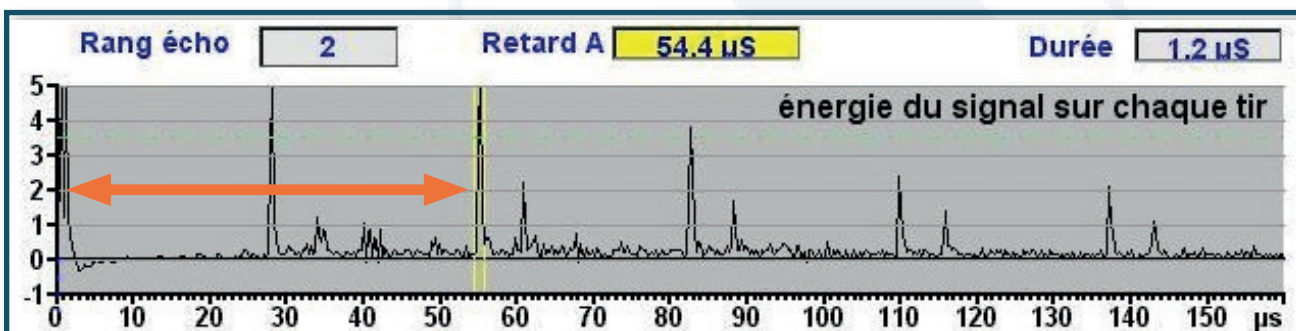
## II Simple measuring mode

Several successive reflections are generally obtained on the testing and bottom surfaces of the screw, if the two surfaces are sufficiently flat and parallel. In SIMPLE measuring mode, the measurement is taken between the emission pulse and a bottom echo.

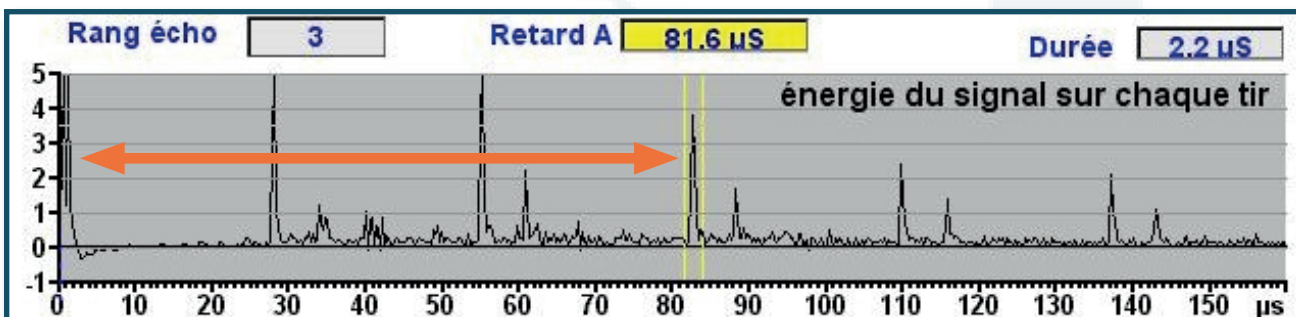
Generally, the first bottom echo is used:



But the second



or third, etc., can also be used.



The more distant the echo is, the greater the risk that it will be weakened and deformed, and therefore difficult to process.

However, the relative accuracy of the measurement improves in proportion to the rank of the echo selected. The most favourable compromise must therefore be chosen. This is where the know-how of the operator who carries out the initial configuration of the system comes into play.

## Processing the echo

An echo more or less takes the form of a damped oscillation, at the resonant frequency of the transducer + screw testing surface assembly, that is, 10 MHz generally. It is generally a few hundred nanoseconds wide.

The required resolution of the measurement is in the order of one nanosecond.

**The system therefore has to determine a characteristic point on the signal. The time will be measured on this specific point.**

Previously, the point at which the signal crosses a pre-determined tension threshold was used.

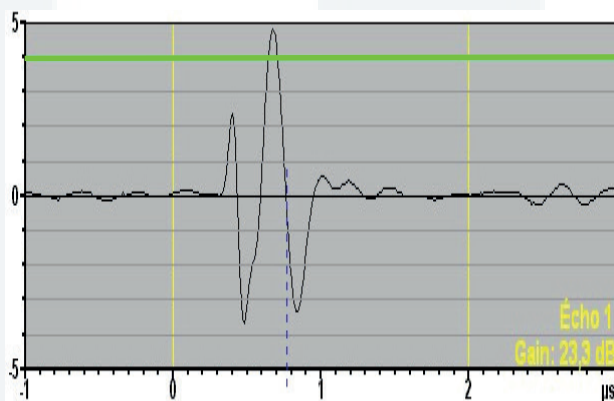
However, the temporal position of this point was affected by the inevitable variations in the amplitude of the signal.

As a result, nowadays the zero-crossing point of the signal is used, which is practically unaffected by the amplitude variations of the signal.

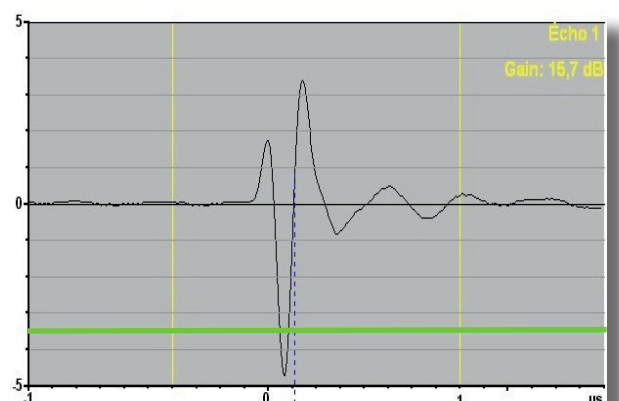
The operator selects a threshold (shown in green below) during initial configuration of the device.

This tells the system the signal arch chosen to determine the next zero-crossing point (shown below by the dotted blue line) at which the measurement will be taken.

As appropriate, we can use...  
... a positive arch...



...or a negative arch... of the signal:



This choice is made solely during the initial configuration of the device, and it relies on the operator's know-how. Then, during on-site measurements, possibly by a less skilled operator, the system will apply the recorded set-point, without any intervention by the operator being necessary.

# The influence of temperature

The temperature of the assembly has a huge impact on the ultrasonic length measured. It changes both:

- ↳ The mechanical length of the screw
- ↳ The propagation velocity of the ultrasonic wave

A variation of just a few degrees is enough to cause errors of 10 or 20% in the tension measurement of a standard assembly.

You just have to handle a screw for a few minutes whilst observing the measurement to see this.

The effect of temperature variations must therefore be corrected. To this end, a preliminary temperature calibration will be carried out (with the system itself) to determine the variation in ultrasonic length (in ns/°C) as a function of the temperature variations.

As this relationship is practically linear (another bit of luck!), **the temperature coefficient  $\beta$**  of the assembly is determined in a simple manner.

The measuring system will be fitted with a temperature probe and will automatically make the corresponding correction during measurement.

The system resets the final length measurement to the temperature of the initial length measurement by applying the **coefficient  $\beta$** .

It then calculates the tension, reset to this initial temperature, thus eliminating the influence of the temperature.

The approximation performed in this way is more than sufficient in terms of the required accuracy of the tension measurement (in order of 1 %).

## The advantages of simple mode

- › It's simple !
- › The system only has to process one echo.
- › It can be used even if there is only one echo.

## The disadvantages of simple mode

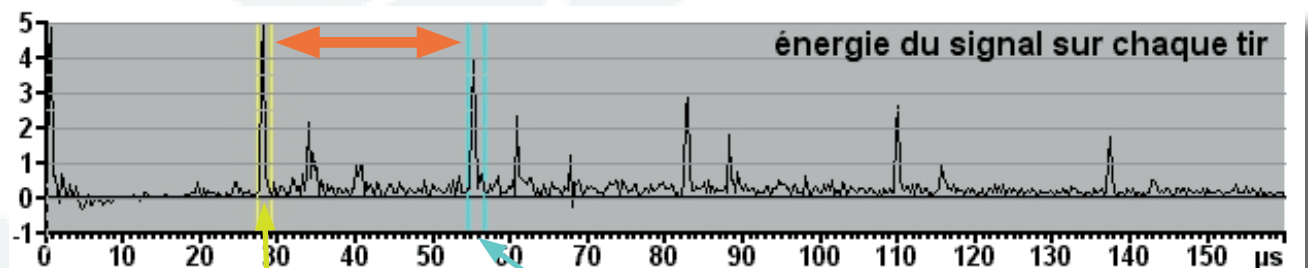
The measurement can be affected by a variety of causes of errors:

- › Length of the cable used (which can vary over time)
- › Variable thickness of the coupling fluid
- › Dispersion in the transducer
- › Possible thermal dispersion from the measuring electronics

These errors are particularly prejudicial if changes in an assembly are being monitored over time. To overcome these causes of errors, it is often preferable to use the differential measuring mode.

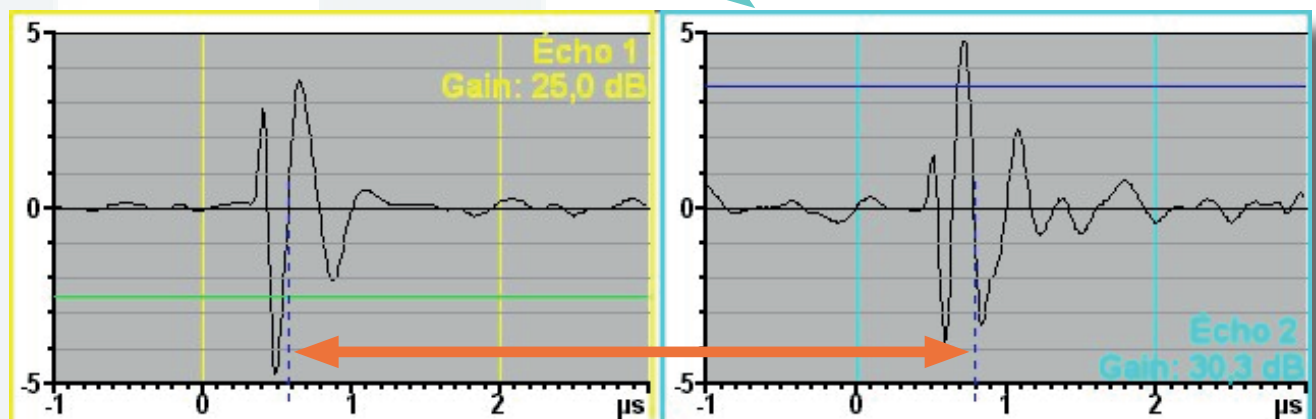
## III Differential measuring mode

This mode consists of ignoring the emission signal and measuring the time elapsed between the return of two bottom echoes, generally the first and second. The measuring system takes two time measurements per zero-crossing of the two echoes.



Zoom of echo A

Zoom of echo B



First bottom echo (TA)

Second bottom echo (TB)

The difference between these two times (zero-crossing of echo B - zero-crossing of echo A) is used as the ultrasonic length.

The path taken by the signal between the two measurements is a simple return journey between the two surfaces, without leaving the material.

This means that all of the causes of error noted above, due to the path of the signal outside the screw, are automatically eliminated.

Differential mode is greatly superior to simple mode, particularly for monitoring assemblies over time, where the long-term reproducibility of the measurement is essential.

**CAUTION** : **TRUE** differential mode requires the **simultaneous** processing of **two echoes**. The system has to control in real time the amplitude of the two echoes selected, with **two different amplification gains**. Only by Traxx !

## The advantages of differential mode

- › It almost completely eliminates all of the main causes of errors that affect the simple mode (cable, coupling, thermal dispersion, etc.).
- › It ensures excellent long-term reproducibility, which is needed for monitoring assemblies over time.
- › It enables data to be exchanged between remote sites or over time, without having to worry about the length of cables or dispersions due to transducers and couplings.

## The disadvantages of differential mode

- › It requires the presence of at least two usable echoes.
- › It processes the second bottom echo which, having undergone **THREE** reflections, can be very deformed and very sensitive to the position of the transducer.
- › The use of this mode requires a certain amount of attention on the part of the operator, to avoid the phenomenon of “arch jump”.

This phenomenon (which also exists in simple mode) occurs when a poorly defined threshold or a very deformed signal makes the system use the wrong measurement arch, thus shifting the selected zero-crossing point by a full period of the signal (for example 100 ns !).

Generally, the error introduced by this “arch jump» is so great that the operator would be unable to miss it.  
There are various algorithms that seem to eliminate the risk of “arch jump”.  
There is still some way to go towards this, and research is underway.

## Specific uses of differential mode

As the system automatically calculates the difference between the two times, a part can be inserted between the transducer and the testing surface.

Its thickness will be automatically eliminated during measuring.

Beneficial uses :

- ✦ Inserting a heat insulator between the transducer and the part if it is very hot (possibly several hundred degrees)

- ✦ Inserting a flexible washer (elastomer) between the transducer and the part if its testing surface is too rough or not flat enough to ensure adequate direct contact with the transducer.

## **N Accuracy of measurements**

With up-to-date electronics, the **resolution** of the measurement is generally one nanosecond or better.

The **accuracy** achieved on the tension measurement is more difficult to establish. The time measuring system can achieve very high levels of accuracy, but physical interference will limit the actual accuracy of the measurement :

- › Modification of the echoes due to differences in the positioning of the transducer, for example rotation.
- › Imperfect flatness and parallelism of the testing and bottom surfaces.
- › Uneven shape of the screw bottom.
- › Metallurgical dispersion between screws of the same type (with the same calibration).
- › Uncertainty over the measurement of the actual temperature of the part, or variable, poorly controlled temperature gradient.

The time measurement will therefore be affected by absolute reproducibility errors, generally of a few nanoseconds.

The uncertainty relating to the tension measurement depends on the measuring range.

### **Numerical examples:**

On a cylinder head screw 150 mm long, the maximum ultrasonic elongation may be in the order of 400 ns.

The **relative uncertainty** on the measurement will be in the order of **1 to 2%**

On a very small screw of just a few mm in length, the maximum elongation will be just 50 ns for example.

In this case, the **relative uncertainty** can rise to **5 to 7%**.

However, by selecting the nth echo when possible, the relative accuracy will be increased n times.

## To sum up,

All causes of error taken into account, this method allows for better than **5%** accuracy on the actual tension measurement, and accuracy as high as **1 to 2 %** in favourable conditions. These levels of accuracy are more than sufficient for current industrial requirements.

# V Different types of use



## Loosening measurements

The initial length is measured with the screw tightened. It is then loosened, and the final length is measured on the loose screw. This gives the tension that existed before loosening. ( $K \times (L_i - L_f)$ ).



## Control of tightening by ultrasonic measurement

The transducer is left in place DURING tightening. The system is then used to monitor the increase in tension in real time. Tightening can be stopped when the desired tension is reached. This ultrasonic control of tightening can be manual (the method used on Ariane, where the operator monitors the tension reading on the device rather than the torque applied) or automatic (control of a screwdriver).



## Dynamic real-time measurements

With a system that can take a measurement very quickly (for example in a few microseconds), the actual stresses experienced by an assembly in operation can be measured. For example, a cylinder head securing stud on a running engine. The stresses experienced by the assembly, for example as a function of the crankshaft angle, can thus be mapped.



## Use in plastic domain

The method can be used in the plastic domain of the material, beyond the elastic one, if certain methodological precautions are taken. This point is outside the scope of this presentation, and can be covered elsewhere.



## Continuous monitoring

The behaviour of an assembly can be monitored constantly, with the transducer and system remaining in place. This (future) method will be used to detect problems before they occur on particularly critical assemblies, and thus avoid dangerous and/or costly breakages.

The system will be able to trigger a remote alarm.

## Examples of applications :

- › Cranes
- › Heavy vehicles (public work)
- › Bridges and civil engineering structures
- › Ski lifts
- › Heavy industry (rolling mills)
- › Power Stations, gas turbines
- › Automotive industry
- › Aviation
- › Ships
- › Rail

The possibilities are endless...



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