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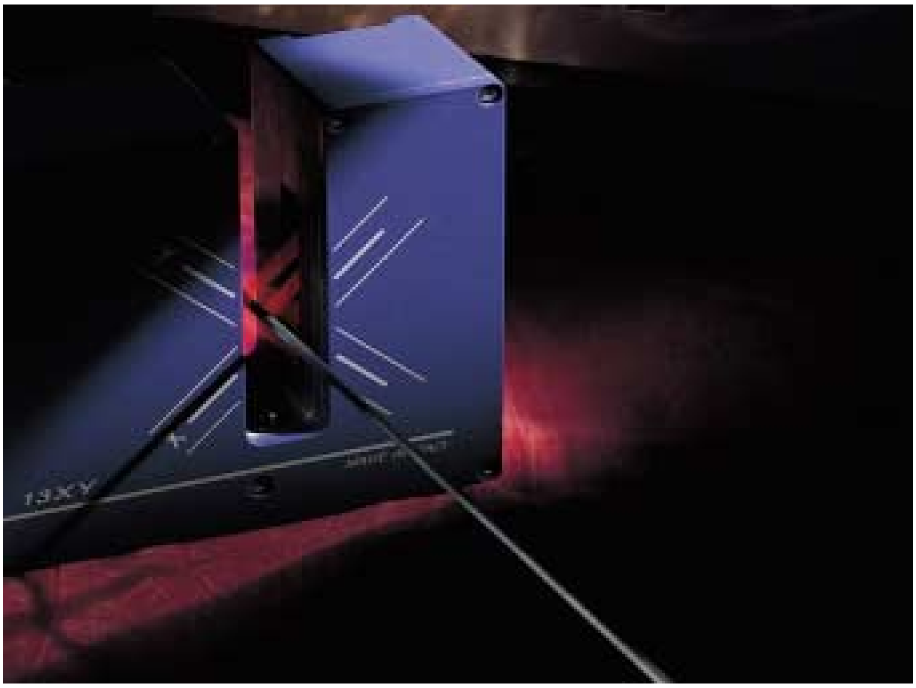

The Continuous Measurement of The Diameter of the Steel Wire Intended for Steel-Cord

SUMMARY:

- The Advantages of Continuous Diameter Measurement
- The Wireline System for
- On-Line Measurement
- Important Results Obtained At Pirelli

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1 - Introduction

The ever-increasing demands to improve wire quality and at the same time contain, if not reduce, manufacturing costs are undoubtedly dictated by the need to maintain a leadership position or introduce new competitive advantages in the face of emerging competition.
Nowadays, the measuring instruments that are required in order to keep the various parameters which characterize the wire and which ultimately determine its quality under control are essential tools for analyzing and thus optimizing the production process.
It is, of course, obvious that any process optimization operation initially involves an analytical phase which should start with the measurements made on the product, on a continuous basis or by means of samples; action cannot, of course, be taken without reliable data.
From being passive components which were only suitable for monitoring the process (for analysis and certification), many measuring instruments are now becoming active components also, in that the results of their measurements determine the control tasks (feedback) or intervention (automatic if possible, or manual) in the process itself in order to improve its efficiency.
In such case, corrective action based on incorrects data from faulty or unreliable measurements can, paradoxically, produce an effect that is the opposite of what desired, and so reliable measurements are absolutely essential. Nowadays there is a wide range of instruments capable of measuring various wire parameters; in view of the type of variable to be measured, they largely lend themselves to laboratory or other off-line measurements (metallography, hardness meters, tensile machines etc.).

In this case the analytical process which will determine subsequent intervention in the process will be of the statistical type, based on the processing of measurements taken on samples (S.P.C, Statistical Process Control).
Other parameters can, however, be measured on a continuous basis, on-line: this is true of the diameter of the wire which can now be measured with a high degree of accuracy by various types of optical instruments available on the market.
The trends relating to this type of instrument, particularly laser scanner gauges, will be analyzed below, with specific reference to their application for measuring the steel wire intended for steel-cord.

2 - The Advantages of Continuous Diameter Measurement

As well as greatly increasing the number of samples on which the analysis is made, continuous wire diameter measurement makes real-time production control possible. The immediate stoppage of the drawing machine before the programmed dimensional tolerances are exceeded enables a wire with no diameter faults to be produced. This thus affords the absolute guarantee that all the product supplied to the client will be to specification, thus eliminating any risk of rejects or complaints.
As is known, the variability of the final diameter of the wire largely depends on the wear on the die, which causes a gradual increase in diameter; together with the other drawing parameters, the tolerance limits for the diameter determine the die's service life.
In its turn, this is a parameter that is not known with absolute certainty a priori; even if we assume that all the drawing conditions (speed, reduction, lubrication etc.) are kept constant, dies of the same type will wear in a similar but not identical manner, thus producing a characteristic curve with a Gaussian distribution, with a mean life and a standard deviation. (Fig. 1)

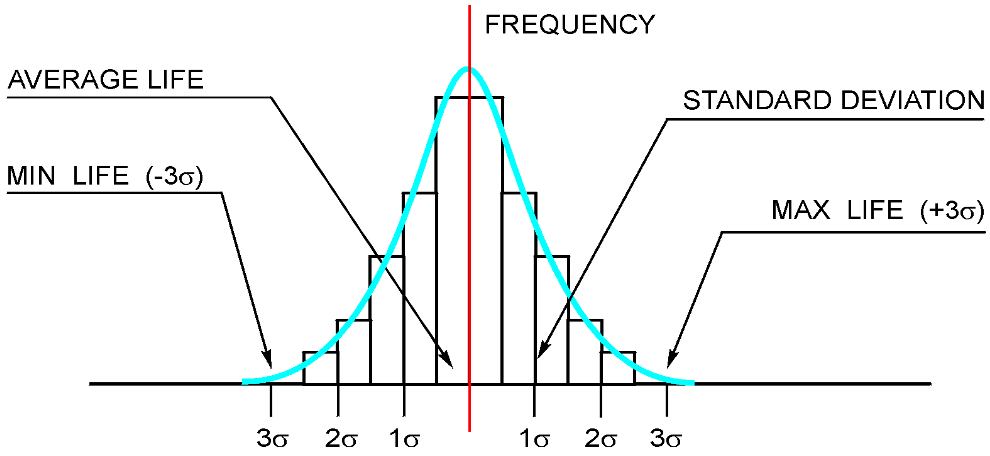

Fig. 1 - Life of the die, tons

If then becomes clear that the three objectives of

1. **gradually reducing dimensional tolerances**, so as to gain new competitive advantages,
2. **producing with zero rejects**, to guarantee product quality, and
3. **maximum die use**, for process economy reasons

are irreconciliable, if we exclude continuous, or at least very frequent, diameter control.
Clearly, only continuous monitoring can determine the limits of use of each die with absolute accuracy and at the same time guarantee that there will be no risk of drawing wire which is off-tolerance.
The choice between a continuous control system and manual sampling essentially depends, of course, on the frequency with which checks need to be made in order to ensure compliance with the tolerances. Continuous control will obviously be necessary when the considerations outlined above and the specific working conditions required sample-taking that is so frequent as to be incompatible with production requirements or too onerous from the point of view of the labour involved.

Where heavy reels are produced (100-200kg), and where it is only possible to check the diameter at the end of reel, with the drawbench shut down, and assuming a typical die service life between a minimum of 400 kg. and a maximum of 800 kg., continuous monitoring is absolutely essential; otherwise the risk of having to reject an entire reel because the diameter was off-tolerance, and only at the end of the reel, would be intolerable!
Nonetheless, even where the lower weight of the reels (15-30kg) permits manual diameter sampling with a sufficiently high frequency to guarantee compliance with tolerances over 100% of the product (and restrict any rejects to a single reel), the use of on-line measuring instruments is also of interest for reasons of economy.
Consider, for example, that a 15 kg reel of 0.30 mm wire approx. 20m/s is produced in about 20 minutes. This is the diameter control interval, an operation which needs to allow at least one minute per man, time that is essential for zero - setting the gauge on the plug gauge, locating the wire, taking the measurement of diameter and ovality (by rotating the gauge), noting down the result and repositioning the micrometer.

Assuming production for 16 hours a day and an average of 250 working day per annum, in the course of a year the diameter checking operations on a drawbench ad up to at least 200 man hours!

In both cases, of course, and regardless of the final weight of the real, automatic diameter checking is essential if it is desired to use drawing machines with automatic collection reel change.
In addition to the considerations just described, further important advantages accrue from on-line measurement compared with manual sampling:

- **Objective and reproducible results**. All manual measurements always involve a subjective component related to the operator's skill: automatic systems, however, are entirely free from this type of error and provide objective and reproducible data.

- **Greater accuracy**. Generally speaking it is very difficult to obtain accuracy better than ±2 μm with manual systems: in contrast, the best laser diameter measuring instruments permit this limit to be bettered, reaching ±0.2/±0.5 μm in the diameter range relevant to this application, which is between 0.1 and 1 mm approx.

- **Data acquisition and production traceability**. This aspect is gaining in importance, particularly in view of the growing spread of Quality Certification Systems.

On-line diameter measuring instruments can easily be integrated into data acquisition systems, whether already installed or scheduled, so as to provide the information relating to the progress of the diameter of the wire produced by each drawbench and within each individual reel in real time and without additional cost. This latter possibility, in particular, of "marking" each reel with the wire's actual diameter, enables reels to be selected with different diameters but within the tolerance range.
This function can be particularly useful in cording, where cords are required with weight/metre that are more uniform than would be possible by joinin the individual wires in a casual manner. Consider, for example, a cord with n wires of diameter Φ: if the tolerance on the diameter of each wire is $\Delta\Phi$, the resulting percentage area (and hence weight/metre) variation will be:

$$100 * \frac{\Delta A}{A} = 100 * 2 * \left(\frac{\Delta\Phi}{\Phi}\right) * n$$

A cord consisting of three 0.30 mm wires with a tolerance of ±0.003 mm, for instance, would have a final weight/metre tolerance of ± 6%.
Clearly, "intelligent" joining of different-diameter wires would enable this tolerance to be reduced substantially, even though this process may introduce a further complication in production and warehouse management.

The assessments of economic convenience and the return of investment needed in order to equip the drawbenches are a direct result of the above, together with consideration relating to management and production, which can also vary considerably according to the specific nature of each company.

It is therefore easy to understand that for the purposes of making the ultimate choice, the fundamental factors to be considered in each case are both the unit cost of the measuring instruments and their capacity to work in the actual production environment so as to ensure that the stated objectives are achieved.

3 - The Wireline System for On-Line Measurement

In the past it was precisely these two latter aspects, cost and the specific characteristics of the equipment available on the market, which discouraged widespread application of on-line diameter measurement on drawbenches for fine wire intended for steel-cord.

AEROEL, a company which has been working in the laser diameter measurement since 1980, has taken up this challenge and has recently concentrated some of its design resources on developing a laser gauge for specific characteristics for use in drawing and particularly on wet drawing machines for producing steel wire for steel-cord.
Results were not slow in coming and in the Spring of 1992 the first WIRELINE Laser Systems were available, they were used for field trials and acceptance tests at major European steel-cord producers, including Pirelli Tyres' factories at Figline Valdarno, Italy, and Merzig, Germany.

3.1 - General Description And Operating Principle

The WIRELINE system essentially comprises an ALS12XY laser gauge, an IBU electronic unit and applications software installed inside the unit (fig. 2)[1].
The ALS12XY gauge uses the traditional principle of optical measurement by scanning. A thin laser beam emitted from the transmitter scans the measuring range at high speed, intercepts the wire to be checked and projects the shadow towards the receiver. By measuring the duration of the shadow, and as the speed of the laser beam is known, it is possible to determine the diameter of the wire with a high degree of accuracy (Fig. 3).
The transmitter is designed to generate two laser beams which cross a 90º, to measure the wire along two orthogonal directions, X and Y, so that any ovality of the product can also be assessed.
Because the transmitter's optical system generates substantially parallel laser beams, the reading of the diameter is not influenced by the wire's position because it is within the measuring range (13x13mm).

The light and shade pulsed collected by the receiver are converted into an electrical signal and transmitted to a separate electronic unit of the IBU type, where a microprocessor processes the signal so as to obtain the diameter along the X and Y axes.
The electronic unit then allows the measurements to be displayed and the tolerances programmed, generates alarms signals, processes the reel statistics and interfaces, via a serial line, with external computers and/or data acquisition systems.

3.2 - Important Technological Aspects

Although this is not the place for a detailed description of the WIRELINE System, for which readers should refer to the specific technical documentation, we believe it is essential to emphasize a number of basic and innovative features of the ALS12XY gauge which have made possible its widespread application on drawbenches for steel - cord wire.

3.2.1 - Why Measure On Two Axes?

Although seemingly in conflict with the need to keep the cost of the gauge within acceptable limits, this feature has proved to be of fundamental importance. Although it is definitely known that every wire has an ovality, which may be more or lees marked according to possible imperfections or misalignments of the die, a correct dimensional measurement of the wire cannot exclude this aspect a priori. In fact, a reading of a diameter within tolerance along a single axis cannot ensure that the dimension of the wire, measured over all the 180º, will be within tolerance.

Having two measurements instead of only one therefore represents an enormous advantage in itself and increases the probability of correctly picking up an ovality that is off-specification.

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[1] Today the new ALS13XY dual axis laser gauge replaces the previous ALS12XY model. in WIRELINE SYSTEM.

Fig. 2: The Wireline System

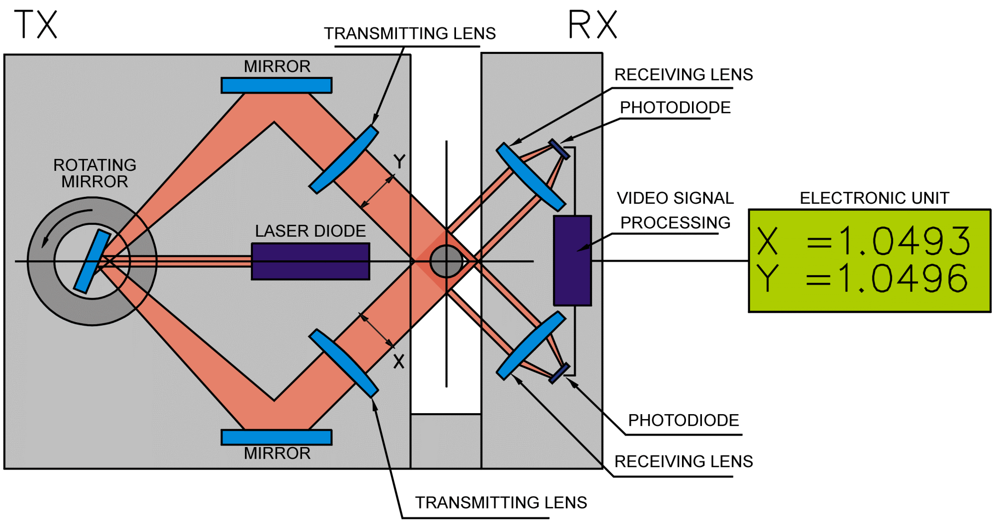


Fig. 3: Operating Principles

We also know, however, that even with two measurements a 90°, there is no certainty that ovality, expressed as the difference $\Phi_{max} - \Phi_{min}$, can be measured at any torsion angle.

What many people may not perhaps know, however, is that by using the two measurements X and Y made a 90° with respect to each other, it is possible to calculate a mean diameter $\frac{(X+Y)}{2}$ which is virtually independent of the torsion angle and which also enables the area of the cross-section (assumed to be elliptical) to be calculated with optimum approximation, at least so that the ovality will be kept within values which are not excessive and hence in true operating conditions.

Now, because in the final analysis it is the wire's mechanical strength - which is proportional to the area of the cross - section - that is its basic property, the biaxial measurement supplies, directly and with the utmost accuracy, the parameter that determines it, in other words the mean diameter of the wire, independently of the value of the ovality and the torsion angle!

In fact, by using, to calculate the area, the mean diameter measured by a crossed-beam gauge, in other words the value $\frac{(X+Y)}{2}$, it is possible to show that the percentage error in assessing the area, $\frac{\Delta A}{A} * 100$, may vary, according to the rotation of the cross-section, between a minimum and a maximum which is given by the equation below:

$$\left[\left(\frac{1}{4\lambda}\right) * (\lambda+1)^2 - 1\right] * 100 \le \frac{(\Delta A)}{A} * 100 \le \left[\left(\frac{1}{2\lambda}\right) * \left(1+\lambda^2\right) - 1\right] * 100$$

where

$$\lambda = \frac{\Phi_{max}}{\Phi_{min}} = 1 - \frac{\Delta\Phi}{\Phi_{max}}$$

$\Delta\Phi = \Phi max - \Phi min$ = ovality of the cross-section

In contrast, if only one measurement is used to calculate the area the assessment error is within the following limits:

$$(\lambda - 1) * 100 \le \frac{\Delta A}{A} * 100 \le \left(\frac{1}{\lambda} - 1\right) * 100$$

Let us take, for example, a wire with a mean diameter of 0.20 mm, but with 0.002 mm ovality, so that the diameter of the cross-section varies between 0.199 and 0.201 mm.

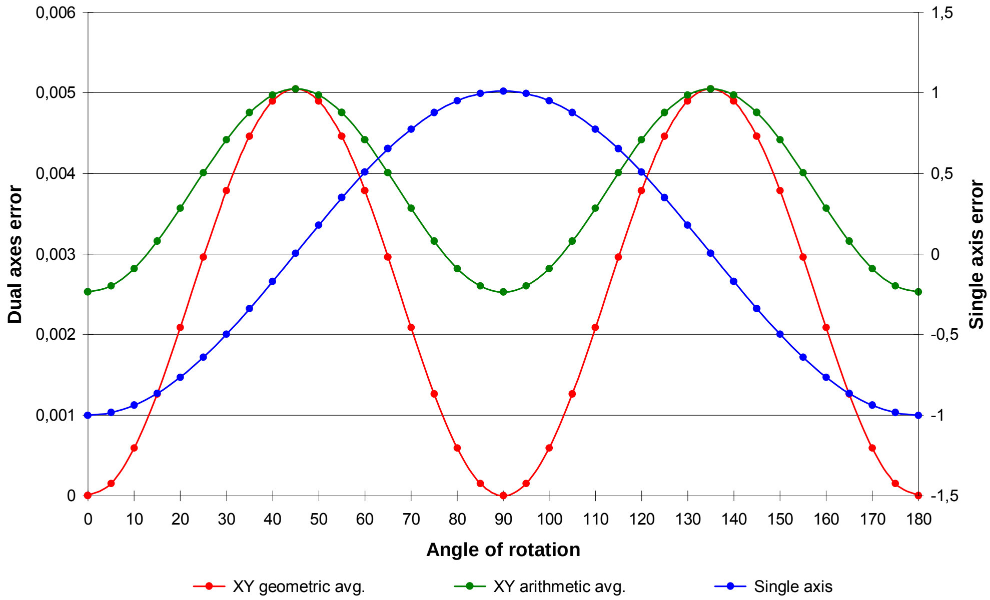
Now, as $\chi = 0.99$, the error that would be made in assessing the area if only one measurement of diameter were used would vary within ± 1%, according to the orientation of the cross-section!

By using a crossed-beam gauge, the error in assessing the area is, however, virtually zero and in any event between +0.0025% inclusive (fig.4)

It is clear that in order to reduce the final scatter of the weight/metre of the cord by a number of percentage points, it is not possible to use single-axis measuring instruments which, of themselves and because of the intrinsic nature of the wire to be measured, and despite being accurate in diameter measurement, cannot nonetheless guarantee sufficient accuracy in the subsequent assessment of the area of the cross-section.

Fig. 4 - % ERROR IN AREA COMPUTING

L = Dmax / Dmin = 0,99



3.2.2 - Measurement Accuracy In Operational Conditions

A further aspect to be assessed when selecting the gauge, which may not be fundamental but is certainly extremely important, is its accuracy and reliability in the actual operating conditions in which it will find itself when installed on the drawbench, downstream of the die and upstream of the collection reel.

In view of the fact that the instrument's purpose is to measure the diameter of the wire so as to check that its value is within tolerances of a few microns, typically ±5µm, the maximum acceptable measurement uncertainty should be less than ±0,5µm, or 1/10 of the tolerance interval.

In its turn the accuracy of measurement is determined by many factors, some of which are characteristic of the gauge, such as repeatability and linearity, whilst others greatly depend on the operating conditions in which the gauge will be situated, such as the presence of dust, fluctuations in ambient temperature, the speed and vibration of the wire.

Linearity

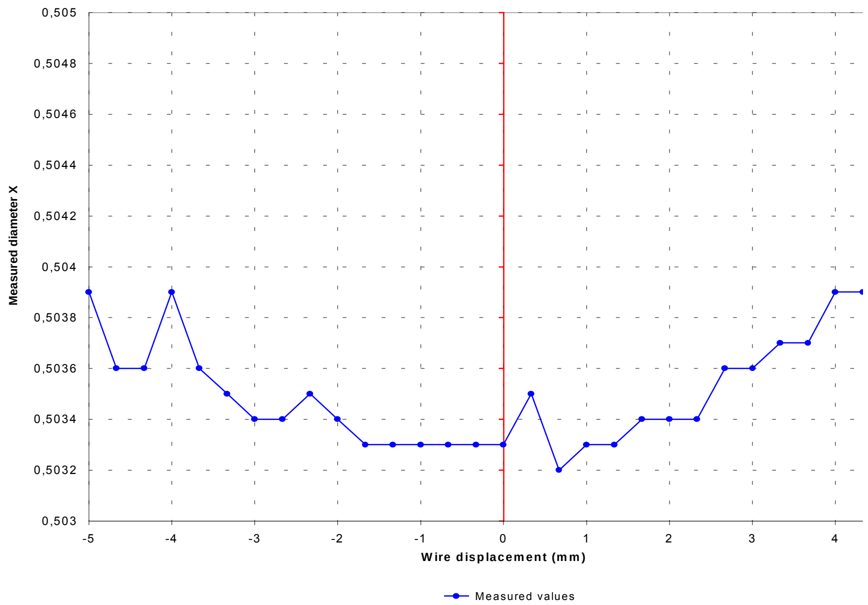
The first type of error is defined as the maximum difference between the true measurement and that recorded by the gauge when the wire diameter varies between the minimum and the maximum value specified and/or when the axis of the wire moves at any point within the specified measuring range; this error is a systematic one and generally varies from gauge to gauge as it depends on imperfections and aberrations in the optical system. (Fig. 5).

Since, in the steel-cord application, the range of diameters to be measured is very limited, typically between 0.15 and 0.75 mm, and the axis of the wire is usually centred in the measuring range (apart from the vibration, which will be dealt below), the non-linearity error is virtually non-existent.

Nonetheless, it is important to know that in any event, in all our ALS12XY gauges the non-linearity error is almost totally compensated for thanks to an electronic linearization technique based on a "map of errors" which is recorded, gauge by gauge, in the course of the production process and stored in an electronic memory in the control unit.

Fig. 5 - VERTICAL LINEARITY (X AXIS)

Nominal diameter = 0.0500 mm



Every measurement is corrected in real time, according to the diameter read off and the position of the wire within the measuring range, according to the specific table in the memory.

Repeatability

Repeatability is obtained from the maximum difference found on a sufficiently large number of measurements relating to one and the same wire sample taken in the same conditions. [2] This error exists in all measuring instruments and becomes evident when the measurement resolution gradually increases: in practice the most noticeable effect is the instability of the last digit on the display!

In laser scanners the non-repeatability error is due to many micro-errors and lack of uniformity (speed of rotation, digital truncation errors, electronic noise etc.) which are randomly added together at every measurement and create this kind of instability. These effects can be minimized by the structural technology and specific design solutions: it is therefore true that repeatability of measurement is a parameter which can be used as an indicator of the "excellence" of an instrument as well as being all important for the purposed of the potential application.

In any event, it is possible to improve repeatability subsequently simply by taking the mean of several measurements as the final result: variation of opposite sign will cancel each other out and the mean value will stabilize. [3] With the ALS12XY gauge, which performs 200 measurements per second (100 on axis X and 100 on axis Y), the non-repeatability of the individual measurement (a $\pm 3\sigma$) is $\pm 3\mu$m: this value drops $\pm 0.3\mu$m taking the mean of 100 measurements, which corresponds to a mean time of 1 second and may subsequently drop to $\pm 0.2\mu$m if the mean time is 2 seconds (fig. 6)

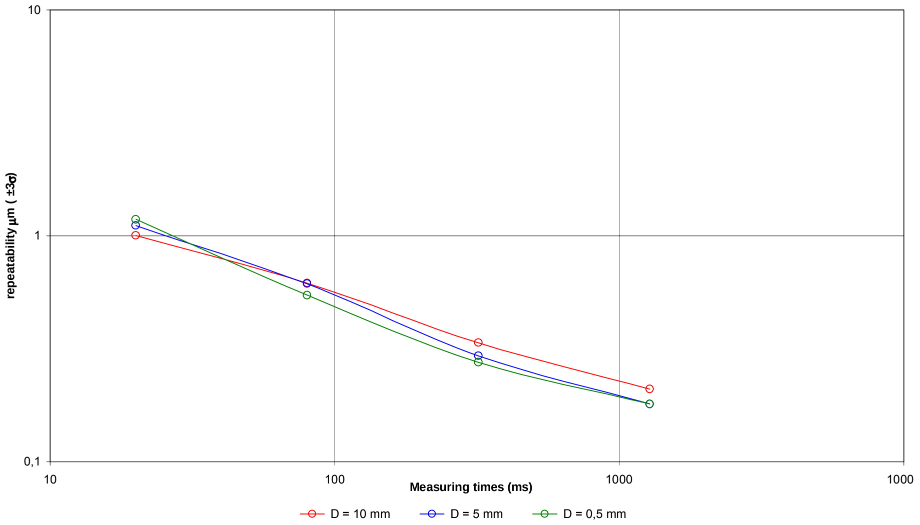
[2] Because the results of a large set of measurements are distributed on a Gaussian curve (normal distribution), repeatability is defined in statistical terms, or is called the difference interval, $\pm\Sigma$, which contains 99.73% (value "a $\pm 2\sigma$") of the findings. The number of measurements exceed 100.

[3] 2 Considering the mean value of a set n of measurements, repeatability improves according to the following equation:

$$\varepsilon_{(n)} = \varepsilon * \left(\frac{1}{n}\right)^{\frac{1}{2}}$$

where n is the number of measurements included in the mean, ε the repeatability of the single measure and $\varepsilon_{(n)}$ the repeatability of the measurements of which the mean was taken.

FIG. 6 - (X+Y)/2 REPEATABILITY
ALS12XY/100/A LASER GAUGE



The only "inconvenience" resulting from this requirement lies in the fact that at the wire has to be measured in rapid motion (8 to 25 m/s), the value read off will be the mean diameter of the wire along a stretch whose length is determined by the product from the speed of the product and the mean time.
In the specific application on drawbenches, this fact can safely be accepted: it will be remembered, in fact, that the purpose of the measurement is to check the die wear, which occurs over relatively long periods of time and definitely in a way which does not produce any variation in diameter in the space of a few tens of metres.

Permanent Self-Calibration

The above satisfactorily describes what we might call "short-term non-repeatability" (which is therefore evident over the space of a few hours), but not what could be termed "long-term non-repeatability" (after days, months, years of operation). Although it is easy to define the long-term stability of a measuring instrument (it is sufficient to specify the test interval), in reality it is difficult and expensive to check experimentally, gauge by gauge, as this obviously requires very long period of time.[4]

Furthermore, for many instruments the outcome may prove to be unpleasant and highlight long-term errors that are unacceptable and inconsistent with practical requirements.
Now, in order to avoid the problem we look at it from another point of view and arrange to re-set or calibrate the instrument from time against reference gauges, so as to zero-set the measurement error (the "drift") periodically and resume the initial condition. But then, of course, the problem promptly returns in another guise: what is the re-set interval that will guarantee that the instrument will remain within the specified non-repeatability limits between two successive calibrations? In these terms also, the answer to the question is a very difficult one.
In many cases, in fact, given that periodic re-setting of the instrument has to be undertaken anyway, it is worth using this procedure to zero-set other errors also, errors which, although not strictly due to the instability of the gauge itself, have nonetheless crept in the interim because of various environmental conditions (such as ambient temperature) or conditions of use (dirty lenses) and which therefore depend on the specific conditions of use. The end user is then asked to take the responsibility for establishing the re-setting interval according to his specific working environment.

[4] We might therefore ask: what is the point of giving definitions and supplying the resultant specifications which cannot be checked in a practical situation on a day to day basis ?

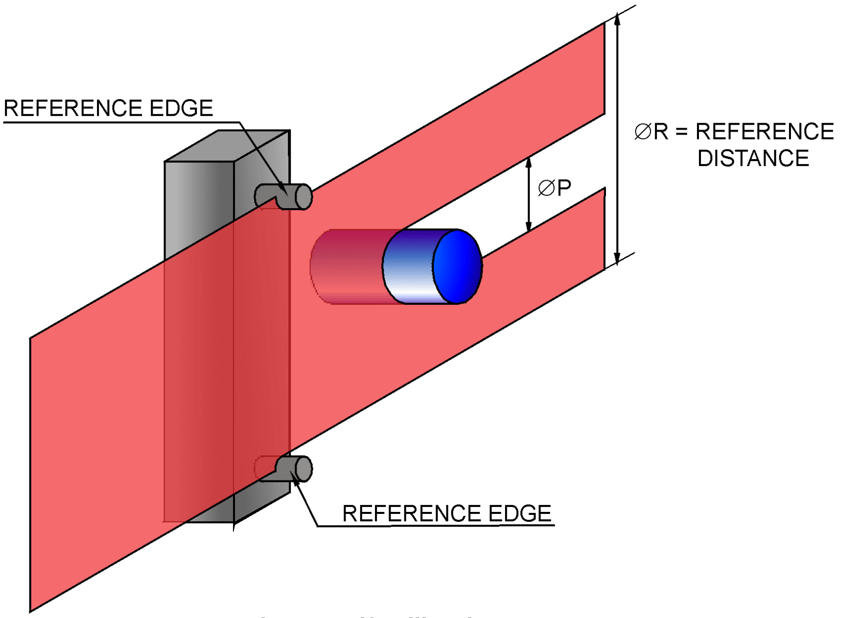


Fig. 7 - Self calibration system

To avoid this kind of problem the ALS12XY gauge uses an innovative self-calibration system which guarantees the permanent calibration of the instrument and cancel out any short-and long-term measurement drift.

Specifically this is a genuine mechanical master [5], equivalent to a steel plug gauge, installed in the gauge at the end of the entire optical chain so as to be measured with every scan, together with the wire to be measured.(fig.7) The measurement of the wire is constantly compared with that of the plug gauge, whose dimensions are known: this means that the instrument is automatically re-set 200 times a second!
There is clearly no reason precisely to repeat the same operation with another outside gauge: it might only be necessary at the time of installation, so as to "reconcile" the read-out of the gauge with the user's plug gauge once and for all.[6]

[5] Actually it is two cylindrical pins, a known distance apart, on a steel base.

[6] By measuring different certified plug gauges with the same gauge it is possible to record differences as small as 0,5 µm between the various values, because of the measurement uncertainty permitted by the Certification Authority (usually ± 0.25 µm)

Insensitivity To Ambient Temperature

The special self-calibration system based on a steel plug gauge also enables the measurement error due to ambient temperature fluctuations to be fully compensated for: as the master in the gauge and the wire to be measured have the same coefficient of linear expansion they will be subject to the same proportional expansion and the gauge reading will not change when the ambient temperature does It can in fact be shown that the total variation in diameter read by the gauge $\frac{\Delta\Phi}{\Phi_0}$ is the sum of two contributions, one due to the true expansion of the wire and the other, of opposite sign, linked to the expansion of the master in the gauge:

$$\frac{\Delta\Phi}{\Phi_0} \cong \alpha_f * (T_f - T_0) - \alpha_r * (T_a - T_0)$$

where

α_f = the coefficient of thermal expansion of the wire

α_r = the coefficient of thermal expansion of the internal master

T_f = the temperature of the wire

T_a = the ambient temperature

T_o = the reference temperature, 20 °C

since $\alpha_f \cong \alpha_r$ the above formula can be simplified and becomes:

$$\frac{\Delta\Phi}{\Phi_0} \cong \alpha_f * (T_f - T_a)$$

Therefore the read-out error is proportional to the coefficient of thermal expansion of the wire α_f and to the difference between the temperature of the wire T_f and the ambient temperature T_a.

The only error related in any way to the temperature depends on the fact that, because of the heating in the course of drawing, the wire is usually at a higher temperature than ambient.

Given that for steel $\alpha \cong 11 * 10^{-6}$, it will be seen, also assuming the wire is heated to a good 100° C, that the variation in diameter $\Delta\Phi$ would be of the order of $0.0001 * \Phi$, or 1 μm for a 1 mm wire and 0.3 μm for a 0.3 mm wire.

Furthermore, because the heating of the wire depends on the characteristics of the process (diameter, reduction, speed, lubrication etc.) it is easy to understand that this type of error can be deemed, for any type of wire, to be a constant which can easily be taken into account when programming the nominal diameter and the tolerances. (fig.8)

Immunity to Contamination

One of the most difficult problems encountered when the ALS12XY gauge was being developed was undoubtedly that of finding a valid way of making the gauge immune to the effects of dust or other contamination on the optical windows.

It is, in fact, well known that the weakness of all optical instruments is their inevitable susceptibility to contamination and, in general terms, any contaminant (dust, droplets or water or oil etc.) which is deposited on the optical windows and gradually causes the signal to decay until the instrument is totally "dark".

And drawing is one of the environments that is least suited to the use of optical instruments on a general basis, because of the presence of dust or lubricant spray at the outlet from the last die, precisely where the diameter measuring instrument is located.

In wet drawbenches in particular, this lubricant spray mixed with metal particles is entrained by the wire and splashed against the laser gauge which, for reasons of space, has to be mounted adjacent to the last die. All attempts to use mechanical screens have been in vain, and in view of the large number of gauges to be installed, the fitting of compressed air-fed pneumatic barriers would have greatly increased the costs to the user, both in the installation phase (pipes, filters, etc.) and in the course of on-going operations (air consumption, filter maintenance etc.).

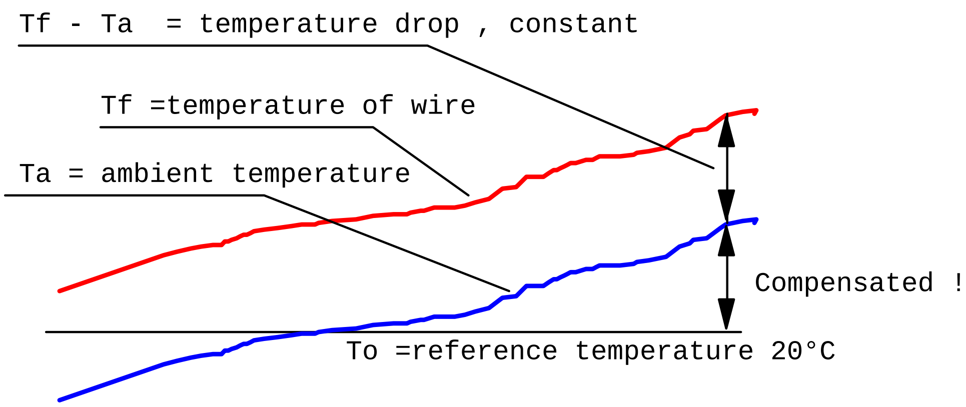


Fig. 8 - Influence of ambient temperature

In actual fact, to be effective compressed air pneumatic barriers need to have a continuous supply of completely dry, oil-free air which can only be obtained after filtration with high - performance filters (activated charcoal filters and pre-filters) which are very costly and need regular maintenance (changing the cartridges). Even the intermitted use of air that is not perfectly clean causes the optical windows to contaminate very quickly indeed and drastically worsens the situation.
Therefore, instead of turning to pneumatic protection systems it was decided to address this problem right at the gauge development stage, and to direct the optical and electronic design so as to obtain a gauge with remarkable resistance to dust. This property was obtained by combining two factors in a synergistic manner.

1) The gauge's optical diagram is designed so as to produce a laser spot of elliptical shape and large area on the optical windows, although it is focused on the wire.
As they are very small compared with the laser spot, individual specks of dust or droplets of emulsion cause only partial attenuation of the total intensity of the signal which is proportional to the ratio of particle area/laser spot area.
Although a large number of dust specks may cause the signal to attenuate appreciably, they will not cause the intensity to vary suddenly in the course scanning.of

2) A new and innovative method of electronically processing the optical signal ("video" signal), which enables the duration of the shadow of the wire (and hence its diameter) to be determined correctly, including on the basis of a signal which is highly distorted and attenuated by the dust, has been developed and introduced (fig.9)
An extremely appreciable results is that because of its specific circuit characteristics, this method means that when there is excessive contamination, uncertain or erroneous measurements cannot be taken: instead, a measurement error condition which requires the operator to intervene to clean the gauge, is reported.
Because of these specific characteristics it has been possible to install the gauges on drawbenches without any need for compressed-air protective devices, and guarantee a minimum cleaning interval of 10 days without any risk of appreciable error caused by the contamination.

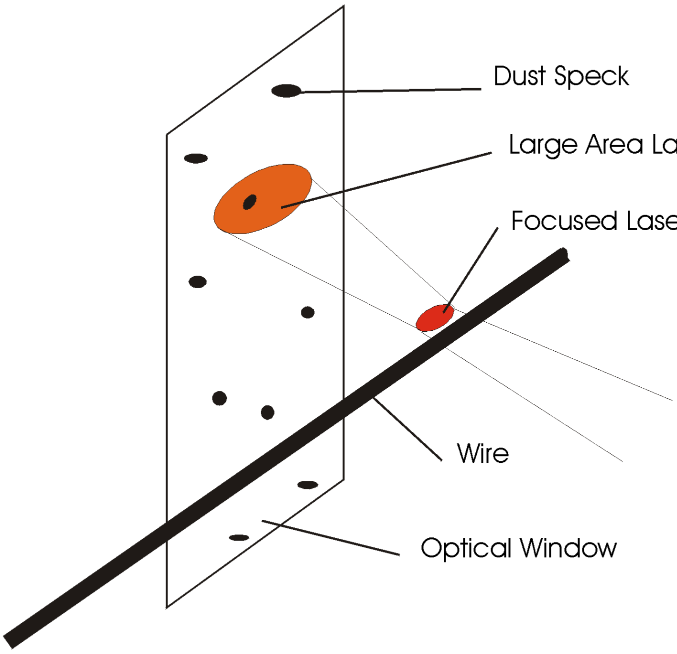
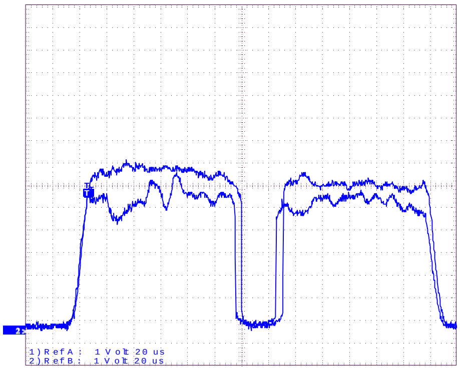


Fig. 9: The optical concept



Video Signal with clean gauge
measured value = 2,0000 mm

Video Signal with dirty gauge
measured value = 1,9996 mm

Fig. 10 - Dust immunity

Insensitivity To Wire Speed And Vibration

A further aspect requiring careful consideration for the specific application is the effect of the wire speed and vibration of the accuracy of the measurement. As far as the former is concerned, as already mentioned above, its only effect is that the diameter read off from the instrument will be the mean value along a stretch of wire which depends on the drawing speed and the mean time (typically 10-20 m to 1 second on average). Because the diameter varies very slowly, we can conclude that the speed at which the wire moves will have no effect on the measurement.
The effect of the vibration of the wire, however, is different and more complex. Generally speaking, vibration can cause three types of concomitant errors which we will analyze separately below.

1. Non linearity error, due to the movement of the wire axis: in the course of the mean time the wire is in different positions within the measuring range. Because the gauge can have a non-linearity error, different measured values may correspond to different positions: the maximum error obviously depends on the extent of the movement and the linearity of the gauge. A priori this error may also be of the same sign, including for symmetrical movements with respect to the centre of the range.

In the space of the mean time, therefore, every single measurement that is taken off-centre may be affected by an error, the summation of which could produce a non-null result and introduce an error into the read-out of the mean diameter as well.
The only possibly way of containing this type of error is to reduce the gauge's non-linearity within acceptable limits and/or reduce the vibration amplitude. With the ALS12XY gauge and the range of diameters of interest to us this error, within a 5x5 mm range, is less than ±0.5 µm, dropping further to ±0.2 µm in a 2x2mm range. On the other hand it is usually possible to reduce the vibration amplitude and restrict it to a few millimetres, simply by guiding the wire either side of the gauge, with two suitable pulleys. In practice this vibration-induced error component was restricted to ±0.2µm.

2. Error due to the inclination of the wire axis.
The vibration of the wire causes the inclination of the wire along the wire itself, between the two guide pulleys. However, as the oscillation usually takes place on the fundamental armonic, the wire axis does not slope if the gauge is located half way between the two pulleys. Also, because this type of error is proportional to the inverse of the cosine of the angle of inclination it is very small angles such as those caused by an oscillation of low amplitude.

3. Error due to velocity compounding.

The vibration generates a velocity component perpendicular to the axis of the wire and in the plane of vibration which may vary randomly in its turn. The component of this "velocity vibration" alone the direction of movement of the laser beam (direction of scanning) combines with the laser beam's scanning speed (which is very high but not infinite) On an individual measurement this velocity compounding effect causes measurements errors which may be both positive and negative according to the reciprocal directions of the velocity which are compounded, according to the following equation:

$$\frac{\Delta\Phi}{\Phi} = \frac{\left(\frac{V_0}{V_L}\right)}{\left(1 \pm \frac{V_0}{V_L}\right)} \cong \left(\frac{V_0}{V_L}\right)$$

where

V_O = the oscillation velocity component along the direction of scanning

V_L = the velocity of the laser beam, which is 65 m/s in the case of the ALS12XY gauge.

In its turn, and assuming a harmonic oscillation, the peak value of the vibration velocity is obtained from:

$$(V_0)_{max} = A_0 * f_0 * \pi$$

where

A_O = the total amplitude (peak-peak) of the oscillation

f_O = the vibration frequency in Hz

From the above equations and taking a vibration at 20 a Hz, of total amplitude 4 mm (±2 mm) and a wire diameter of 0.5 mm we can calculate for example, that the maximum possible error for a single measurement will be about ± □□ṃat worst. Fortunately this type of error is of opposite sign in the two oscillation half-cycles: it is therefore easy to understand that a mean taken from a sufficiently large number of measurements will virtually entirely cancel out the error on the mean diameter. And this is true both where the scanning frequency is higher than the oscillation frequency and the mean comprises several oscillation cycles and in the opposite instance where the scanning frequency is lower than the oscillation frequency, because the mean includes measurements taken at different phase angles and affected by errors of opposite signs.

The only unfavorable situation would arise if the two frequencies or their harmonics were completely equal: this is highly improbable given that even a beat between very simile frequencies is characterized by a slow but continuous variation in the phase angle, which would lead, albeit in a longer mean time, to measurements of opposite sign which are canceled out in the summation.

This can be calculated and rendered in quantitative terms by the following equation:

$$\frac{\Delta\Phi}{\Phi} \cong \pm\alpha * \left(A * f_S * \frac{\pi}{V_L}\right) * G(n,\omega) = \pm\alpha * 0{,}058 * G(n,\omega)$$

where

α = the amplitude of the oscillation (peak-peak), expressed as a fraction of the measuring range ($0 \leq \alpha \leq 1$)

A = the measuring range of the gauge (12 mm)

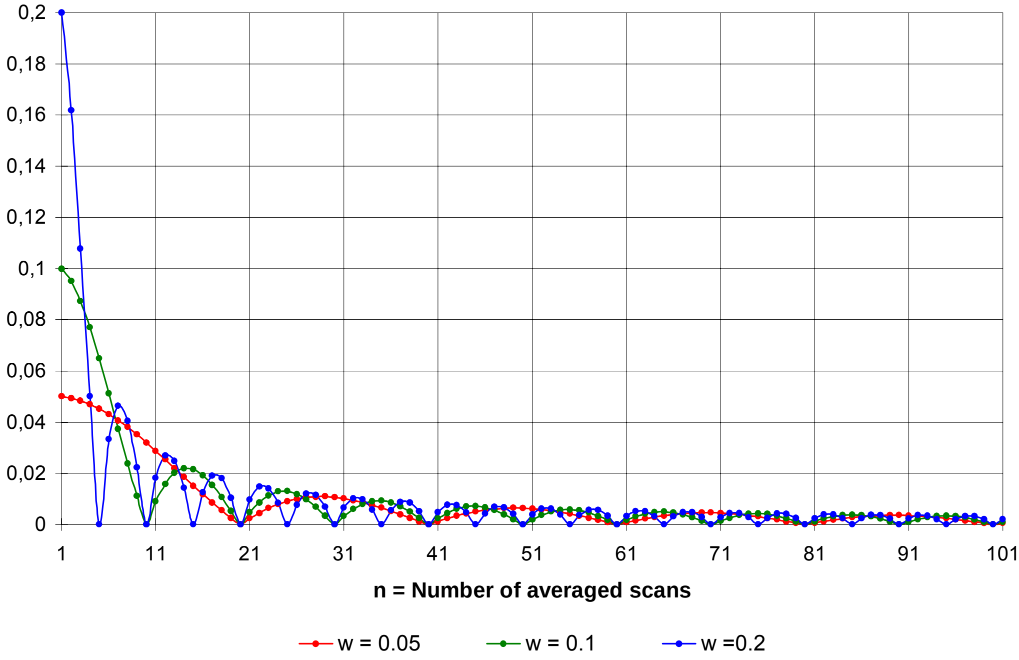
V_L = the velocity of the laser beam (65 m/s)

n = the number of scans in the average

$\omega = \frac{f_o}{f_s}$ = the ratio between oscillation frequency and scanning frequency (100 Hz)

$G(n,\omega)$ = function of n and ω

Fig. 11 - FUNCTION G(ω,n)



The function G (n,ω) can only be calculated numerically - it cannot be expressed in analyticalterms; the following illustration shows the plot of this function calculated for a number of values of ω, as a function of the number of scans included in the mean.

For example: if ω= 0.2, corresponding to a vibration frequency of 20 Hz, and taking an amplitude equal to the entire measuring range, or α = 1, it will be found that a mean of 20 scans already restricts the maximum error $\Delta\Phi/\Phi$ to ±0,0011, i.e. approximately ±0.5 µm for a 0.5 mm wire; if the mean is extended to 100 scans this error drops to less than ±0.1 µm.

4 - Important Results Obtained At Pirelli

In conclusion, it is clear from the above that the ALS12XY gauge now represents a valid response to the demands for on -line diameter measurement which are being expressed by an ever-increasing number of drawers of wire steel-cord.

As further evidence, and by way of "experimental" proof obtained in the field, we are pleased to quote a number of important results at Pirelli, on the basis of extensive use of our Wireline Systems which were installed on more than 130 drawbenches for fine wire (0.15 to 0.75 mm) between 1992 and the present day.

1) It has been possible to reduce the tolerance on the wire diameter from ±0.007 mm to ± 0.004 mm.
2) It has proved possible to use drawing machines with automatic collection reel change, with a consequent improvement of approx. 30% in terms of man hours.
3) Rejects due to non conformity of the diameter have been totally eliminated
4) It has been possible to reduce the variability of the weight/meter of the steel-cord from ± 6% to ± 3%
5) It has proved possible to acquire data in real time and then process them automatically on computers connected directly to the measuring systems
6) The instruments installed have been proved to be 100% reliable.

In conclusion it can be said that the diameter measuring instrument installed directly in-line makes a major contribution to an increase in drawn wire producers' competitive opportunities as well as being an essential part of 100% quality control.
To obtain results which reflect expectations it is, of course, essential to use gauges with a high degree of excellence and which have been designed to operate correctly even in environments which are not usually favorable to their use.

5 - Acknowledgements

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