Ultrasonic extrusion quality monitoring of multilayer HV cables during production – 'A New Vision in Cable Monitoring'

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ABSTRACT

Whether it is in manufacturing existing cables more cost effectively or in designing new cable types, Extrusion Quality Monitoring and Control is a major key to success. This paper presents valuable information about extrusion quality that has never been obtainable before, and is now only available due to the introduction of advanced ultrasonic technology onto the production line. The remarkable fidelity of this new measurement technique not only provides new insights, but also opens the door to new areas of process understanding, cable design & development as well as material savings.

KEYWORDS

Ultrasonic, Extrusion, Quality, Measurement.

INTRODUCTION

Ultrasonic cable geometry measurement is now becoming established on the production lines of some of the world's top cable manufacturers, and the benefits of the very high fidelity and unique information that it provides is already being acknowledged and bearing fruit in terms of the optimization of extrusion line production techniques.

The aim of this paper is to make this knowledge available to a much wider audience, to provide not only an enhanced view of the actual structures that exist within cables, but also to highlight new and powerful production control techniques that are set to play a significant role in on-line production optimization and material usage control.

The operation of the ultrasonic equipment and the format of the results it produces are described in the following sub-section, after which sub-sections relating the characteristics of the cable layer width variations will be presented. Then a further sub-section will consider the stability characteristics of perhaps the most critical of the cable layer interfaces – the inner screen / insulation layer interface, whilst a further sub-section will then consider a totally new approach to monitoring and potentially controlling layer and interface stability, before the findings of this paper are finally summarized.

EQUIPMENT OPERATION AND RESULT FORMAT

The ultrasonic measurement technology, from which the results presented in this paper are derived, is embodied in the product known as UltraScreen, and all the results presented in this paper are derived from data collected from the different types of lines on numerous manufacturer's sites on which this equipment is currently deployed.

To understand the format of the results presented in this paper it is first necessary to understand some key points about the operation of UltraScreen on a production line. UltraScreen is normally positioned just after the end of the CV tube but before the caterpillar, and the extruded cable is pulled through the machine, passing through an internal water bath containing the ring of 16 ultrasonic transducers – as illustrated in Fig 1.

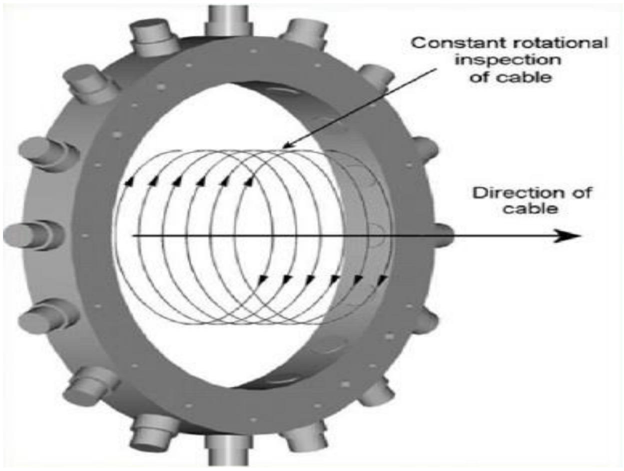

Fig 1 – UltraScreen Operation

As the cable passes though the machine the transducers are sequentially fired so that a complete circumferential set of 16 measurements is completed every 16ms. As ultrasonic analysis detects the interface between two different material types, the data set for each transducer provides the radial position of each of the four interfaces, (water / outer semicon, outer semicon / insulation layer, insulation layer / inner semicon & inner semicon / core) for that sector of the cable to an accuracy of ~10-20 micron. This data set is then used to calculate the widths of the three cable layers, and data from opposing channels is used to calculate the diameter of the cable across these sectors.

Thus, every 16ms the equipment produces a base measurement set of 16 widths for each of the three extruded layers and 8 diameter measurements. At a typical HV line speed of 1m/min, the 16ms scan time means that a new measurement set is taken every ~270micron along the cable over the whole production length of the cable. As part of its integration onto different customer lines, detailed statistical studies have been undertaken to compare the measurement accuracy of UltraScreen against off-line, optical measurement systems. These rigorous studies, which have been used to qualify the measurement system to end user clients, have concluded that there is no statistically significant difference between the on-line, layer width measurements produced by UltraScreen, and the results produced by the off-line, optical systems.

In this sense the measurement sets produced by UltraScreen every 16ms can be envisaged as a measurements of a 'cable slice' some ~270micron thick and, as the base measurement set is also be used to evaluate derived parameters like Concentricity, Ovality, Eccentricity, etc., values for these parameters can also be produced for every cable slice, which opens new possibilities for more exacting production line testing of cables against the requirements defined for these parameters in contractual and/or trade standards.

Within a base measurement set, the measurements produced by individual transducers are termed ‘channels’. There are 16 channels numbered 0 – 15, and aligned so that channel pairs 0 & 8, 1 & 9, etc., are opposite each other. Such measurement data is collected within UltraScreen in files spanning ~25s of run-time and the majority of the figures presented in this paper are produced by the analysis of the data contained in a single such file – of course, in on-line operation, such information would be available for every such file.

INSULATION LAYER THICKNESS VARIATION

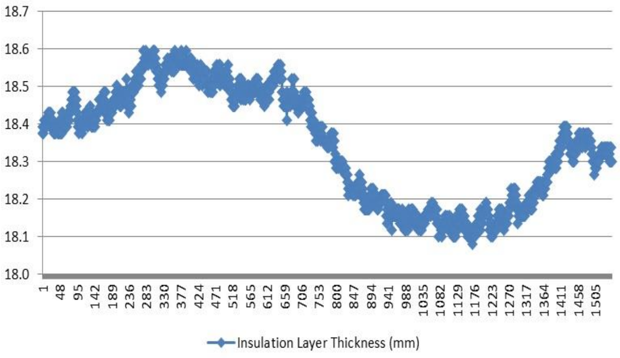

Fig 2 – Insulation Thickness Variation over 0.8m of Cable

Fig 2 presents the thickness of the insulation layer measured in one UltraScreen channel during a data file which, due to the line speed in operation at the time, represents a cable length of approximately 0.8m.

Now what is immediately apparent is that the layer thickness is not constant over this cable length, in that there is a peak–to-peak variation of some 500 micron in the measured layer thickness that occurs over a cable length of ~0.4m.

Thus the first observation that needs to be made is that whilst there seems to be a traditional view that measurement data for cables only needs to be assessed for every metre of production – often using singular values averaged over each metre – this view does not perhaps reflect the variability of the layer thickness variations that actually exist within extruded cables.

For this data set, an average value can be calculated = 18.35mm. However, what is very clear from Fig 2 is that this average value does not accurately reflect the behaviour of the insulation layer thickness over this 0.8m length, and that there are variations in the thickness of this layer that are occurring with scale-lengths far shorter than 1 metre. Further it may be evaluated that, just within this data set, the insulation layer thickness attains a maximum value = 18.59mm, and a minimum value = 18.08mm.

This level of thickness variation is quite typical of HV cable production and thus, this data suggests strongly that any cable evaluations underpinned by an assumption of ‘constant’ layer thicknesses, based on averages over say a metre of cable, are not obviously justifiable!

CONCENTRICITY

One such evaluation is the calculation of Concentricity defined – as in Section 10.6.2 of IEC60840 – as:

(Tmax – Tmin)/Tmax

That needs to be evaluated and checked against a threshold value (= 0.15 in the specification).

And the standard also notes that ‘Tmax and Tmin are measured at the same cross-section of the insulation’.

As noted in the introduction to the paper UltraScreen can calculate the Concentricity of the cable over every cable slice it takes and Fig 3 shows the actual Concentricity measured for the same data set as used for Fig 2.

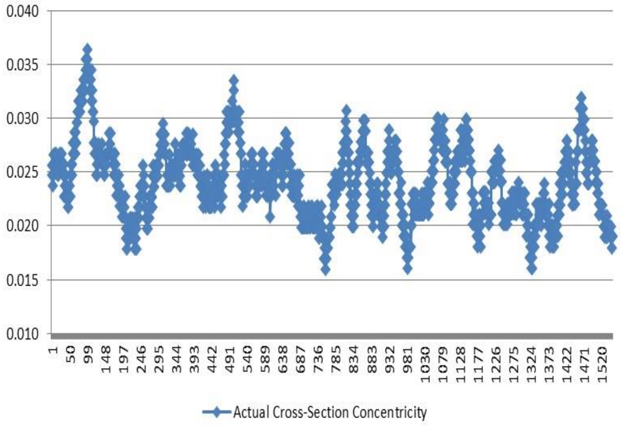

Fig 3 – Actual Concentricity Values

From Fig 3, it is very clear that actual Concentricity varies considerably over this 0.8m section of cable, from a minimum value of ~= 0.016, up to a maximum value ~= 0.036 – so actually a ratio greater than 2 : 1 between maximum and minimum values.

It is also clear that significant variations in the actual Concentricity occur over scale-lengths considerably shorter than 1 metre.

So when the IEC60840 standard notes that ‘Tmax and Tmin are measured at the same cross-section of the insulation’, the implication of the results presented in Fig 3 is that such a cross-section should also be considerably shorter than 1 metre!

A cross-section is effectively defined as being a face cut across the cable perpendicular to the centre line of the cable, however, the industry seems to accept ‘being at the same cross-section’ as being within a slice across the cable perhaps of a width of 1 - 2mm, in line with optical testing techniques - which is actually wider than the cable slice width of ~500micron that characterizes the UltraScreen results presented in Fig 3.

Now if Concentricity is measured based on Tmax and Tmin values averaged over, say, the totality of the 0.8m section of cable presented in Fig 3, then the relevance of this ‘Averaged Concentricity‘ value to the Actual Concentricity value depends upon the consistency of the Tmax and Tmin values over that cable length.

Unfortunately, an inherent effect of an averaging process is to underestimate maximum values and overestimate minimum values which, for a parameter like Concentricity, implies that the use of such values will also underestimate the Actual Concentricity present within the cable.

To investigate this, an ‘Averaged Concentricity’ value has been evaluated for the same data set as Fig 3. This produces a value for the Averaged Concentricity = 0.020, and both this value, and the values for the Actual Cross-Section Concentricities, are presented in Fig 4.

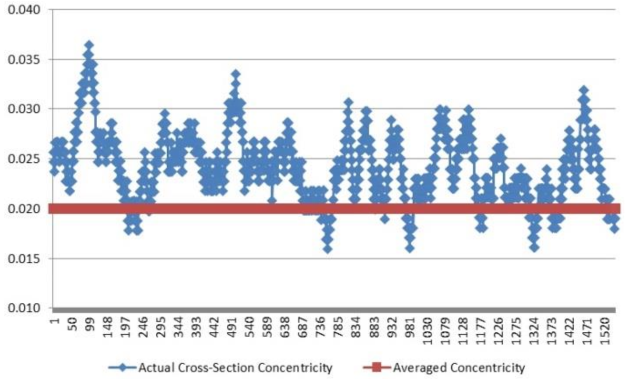

Fig 4 – Averaged v Actual Concentricity Values

As predicted, the Averaged value significantly underestimates the Actual values that occur over this cable length.

This is worrying because, as this is the general result expected for such measurements, then it implies that cables are being verified against this aspect of IEC60840 based on Averaged Concentricity measurements that significantly underestimate the Actual Concentricity values that occur in the cable.

So again, this questions the validity of using such averaged Tmax and Tmin values in such Concentricity considerations and, perhaps even more importantly, whether the use of such values is even compliant with the terms of IEC60840, given that it is difficult, if not impossible, to argue that being ‘measured in the same metre of cable’ satisfies the criterion of being ‘measured at the same cross-section of the insulation’!

KSM MEASUREMENTS OF CABLE GEOMETRY VARIATION

The whole validity of the observations made in the previous two sub-sections, depends upon the acceptance of the base observation re the level of variation in the internal geometry that occurs within an extruded cable with scale-lengths far shorter than 1 metre. And so this sub-section sets out to provide external support for this base observation.

It was noted in the introduction that detailed statistical studies have been undertaken to compare the measurement accuracy of UltraScreen against off-line optical measurement systems. Now, part of this calibration exercise, undertaken against an off-line measurement system – a KSM system in this case - involved scanning a nominated metre length section of cable first with UltraScreen on the production line, and then cutting this section out and taking 10 slices, spread over the metre length, for KSM analysis.

This analysis produced values of the insulation layer thickness Tmax and Tmin for each slice – presented in Fig 5 – from which Concentricity values were calculated – presented in Fig 6. And it should be stressed that the KSM measurement work was independently made by the client’s own laboratory staff, and not by Acuity personnel.

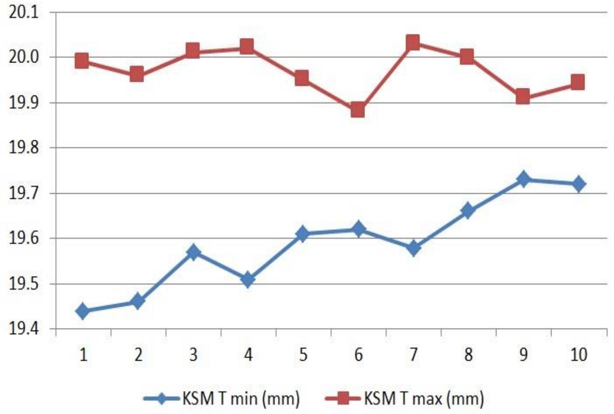

Fig 5 – KSM Measurements from 10 slices over a 1 metre cable length

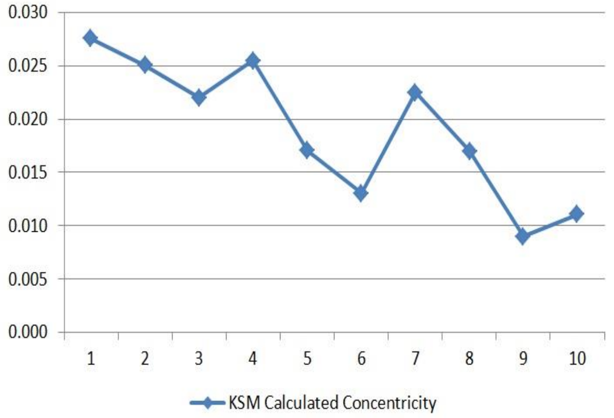

Fig 6 – KSM Calculated Concentricity from 10 slices over a 1 metre cable length

From Fig 5 it may be seen that Tmax and, in particular, Tmin varies noticeably over this cable length – with Tmin seen to vary between 19.44mm and 19.73mm over this metre section. And from Fig 6, this variation in Tmax and Tmin can be seen to result in a significant variation in the Concentricity values calculated over this metre section, which range between a maximum value of 0.028 and a minimum value of 0.009 - so a max to min ratio just in excess of 3 : 1!

Now of course an average value = 0.019 can be evaluated from these calculated Concentricity values, but it not clear that this single value represents this dataset in any meaningful manner.

So these KSM measurements, whilst at a much coarser sampling granularity than the UltraScreen measurements, still re-enforce the fundamental findings of the fine-grained UltraScreen analysis in that they show - via a completely independent measurement schema - that over a metre length of cable:

- There is a noticeable variation in the measured insulation layer thickness Tmax and/or Tmin values.
- The variation in these measured parameters results in a significant variation in the Concentricity values calculated.
- There is no one single value of Concentricity that characterises the totality of this length of cable.

INNER SCREEN SMOOTHNESS

With the level of variation present in the layer thicknesses now established, it is now important to consider the variation that occurs at the interface between the inner screen and the insulation layer. Because the smoothness of interface has become a key issue, presumably because it is at this interface that the maximum radial electric stress field strengths occur and so it is at this interface in the cable structure that the subsequent performance of the cable is most sensitive to the presence of such variations.

In order to discuss this issue a new concept – that of an ‘inner screen / core tube’ – needs to be introduced. This ‘tube’ can be considered conceptually as comprising of the core and the inner screen and, during an extrusion, this tube nominally sits in the centre of the cable but, in reality, wanders about a bit – producing non-concentricities in the cable structure.

This behaviour can be seen in Fig 7, which presents the typical variation, over a ~0.8m cable length, of the radial positions of two opposing insulation layer / inner screen interfaces – in this case channels 0 & 8 – relative to their mean positions.

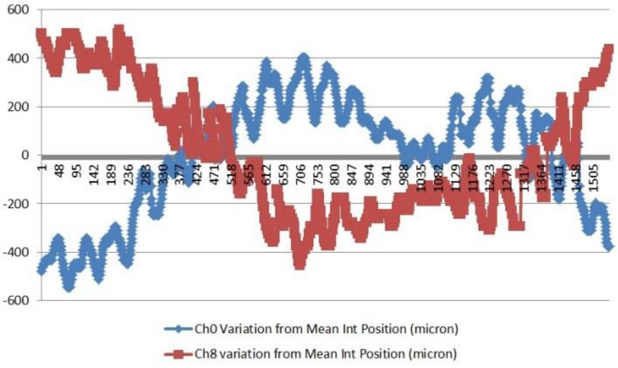

Fig 7 - Opposing Insulation layer / Inner screen Interface Positions

Now, to a first approximation, the two lines on this figure almost look like ‘mirror images’ of each other – not only in terms of the longer-scale structures, but also in terms of the shorter-scale structures.

What this figure shows is that the ‘tube’, consisting of the inner screen and the core, is moving around inside the cable over this ~0.8m length. And as channel 0 is at the top of the cable and channel 8 is at the bottom, then Fig 7 shows that the ‘inner screen / core tube’ was higher in the cable at the left-hand side of the figure, sank lower in the cable around the centre of the figure, before rising up again towards the right-hand side of the figure. Whilst, at the same time, oscillating up and down at a higher rate.

So the position of this tube within the cable can be seen to be varying over scale-lengths far shorter than a metre which, of course, ties up with the layer width variations noted in the earlier sub-sections.

Now whilst to a first approximation, the two lines on this figure almost look like ‘mirror images’ of each other, it is clear on closer inspection that they are not. And that is because in addition to the gross variation of the position of this tube, the tube surface itself exhibits a variation or roughness along its length, and this variation can be isolated to provide a measure of ‘inner screen smoothness’, as presented in Fig 8, which presents the variation in the diameter of the ‘inner screen / core tube’ – for the diameter defined by opposing channels 0 & 8.

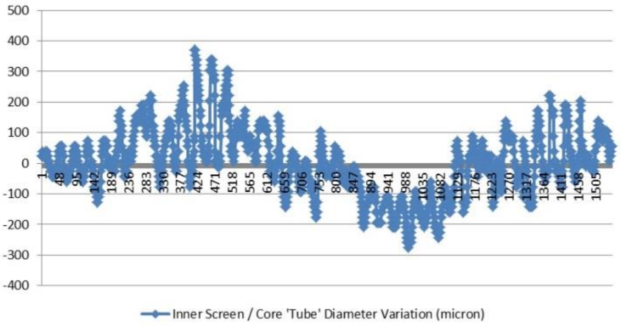

Fig 8 – Tube Diameter Variations

From this figure it may be seen that whilst the shorter-scale variation is still evident, the longer-scale variation is much reduced. Nevertheless, this variation can be seen to produce a peak-to-peak variation in the tube diameter of some ~700micron.

Of greater concern is that the figure clearly shows that the variation in the diameter of this tube is effectively dominated by a rapid sequence of protrusions / fall-ins with protrusion heights anything up to 300-400micron. Given the fine-scale nature of these protrusions, the monitoring and potential control of the level of such inner screen smoothness is now becoming a key issue.

EXTRUSION QUALITY MONITORING

From the previous sub-sections it may now be appreciated that the internal structure of an extruded cable is perhaps far more variable or dynamic than was previously realized. And that, due to the fine-scale nature of some of these geometrical variations it is only now, with the advent of fast-scanning measurement systems like UltraScreen, that this important internal detail can be revealed.

This raises the crucial issues of both how is it best to monitor such variation – both longitudinally along the cable, and circumferentially around the cable, and is it possible to provide a feedback control mechanism that could be used on the production line to maintain a required variation level throughout the course of a production run.

Longitudinal Thickness Variation

As has already been noted, the longitudinal variation in the layer thickness can be evaluated directly from the UltraScreen measurement data, and Figure 9 presents a further exemplar of the typical variation of the insulation layer thickness captured on one channel, which is actually presented as the variation of this layer thickness around the average thickness for that cable length.

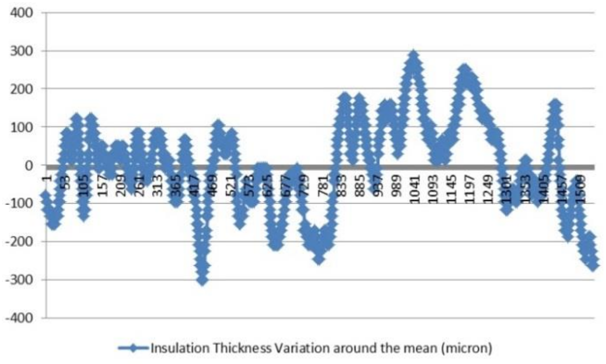

Fig 9 – Insulation Layer Thickness Time Series Data

From this figure it can be seen that again this variation is characterized by a fine-grained structure, with the thickness varying peak-to-peak about 600micron over this length of cable and, of course, this variation can be characterised by evaluating its Standard Deviation, S.D., which equates to ~118 micron for this channel.

Circumferential Thickness S.D. Variation

Now as UltraScreen measures 16 such channels, the S.D. of the extrusion variation for each channel can be evaluated and displayed as in Figure 10.

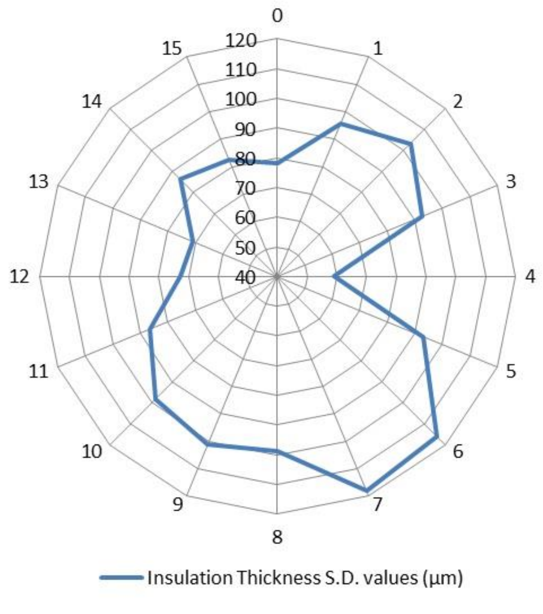

Fig 10 – Insulation Thickness S.D. values around the cable.

From Figure 10 it is clear that monitoring the extrusion quality of the insulation layer in this detailed manner, shows clearly that the extrusion quality is not consistent around the cable, with the minimum S.D. being measured at about 60micron, whilst the maximum is about 120micron.

Also it is clear that this variation in S.D. value is not random, but has a clear pattern indicating, in this case, that the cable sector, spanned by channels 5 – 7, has an extrusion stability that is worse than any other sector.

This sector can be related back to the actual geometry of the extruder head, to identify the aspect of the extruder head responsible for the increased extrusion instability.

Thus monitoring the circumferential variation in the extrusion quality in this manner not only provide a means to quantify the level of variation in different sectors of the cable, but also provides a feedback mechanism that could be used to explore the impact of changes in the extruder head on the circumferential extrusion consistency.

Longitudinal Frequency Domain Analysis

Whilst the time series shown in Fig 9 gives a very good overview of the longitudinal variation in the layer width, one fact that is clear when considering extrusion quality – either in terms of the stability of layer widths or the smoothness of the interfaces between the layers – is that the variations observed are not random fluctuations but demonstrate noted ‘periodic’ structures. And this fundamental fact is clearly illustrated by the figures presented in this paper.

This is perhaps to be expected given that, at a fundamental level, an extrusion head operates as a dynamic control system that is seeking to control the even extrusion of multiple layers. However such observations question whether the best way to characterise such variations is in the classical time domain manner – utilising metrics such as Means and Standard Deviations – or whether a more natural framework to assess extrusion stability actually lies in the frequency domain?

Using Fourier Transform analysis to extract these periodic structures provides a very insightful, and potentially very powerful, way of assessing such instabilities in the extrusion process, as not only does such processing facilitate the quantification of such variations, but it also facilitates the identification, and thus potential control, of such extrusion instabilities. For once a mode of variation is noted, its periodic characteristics may be related back to a particular aspect of the operation of the extruder head, and thus control can be exerted over this variability by an adjustment in the extruder head settings.

To illustrate this, the time series presented in Fig 9 has been analyzed using a Fourier Transform (FT), to identify the frequency characteristics of this extrusion variation, and the analysis of this data set is presented in Fig 11.

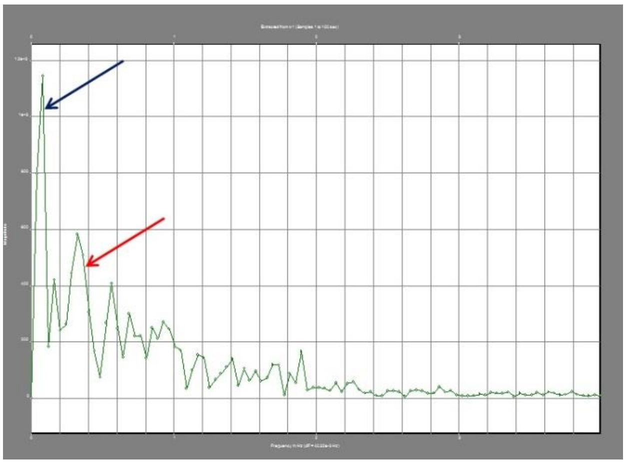

Fig 11 - Insulation Layer Thickness Variation, Frequency Analysis (0 – 4Hz)

This shows the frequency characteristics of the data in the frequency band up to 4Hz, with this data scaled to accurately reflect the 16ms sampling period fundamental to the UltraScreen time series data collection.

(Note that this figure would be zero across the whole of this frequency range if the extrusion was perfectly stable.)

However what this figure clearly shows is that the variation in this extrusion is not 'noise-like', i.e. spread randomly across this frequency range, but is clustered into 'dominant frequency modes'.

In detail it can be seen that there is a large peak in this data (blue arrow), at the left hand side (low frequency end) of the FT 'Spectrum' presented in the figure.

The frequency of this peak is at ~= 0.08Hz which implies a Periodic Time (PT) for this oscillation of ~12.5s, but as there is also quite a large response also at ~= 0.04Hz, this FT response suggests that the 'mechanism' producing this oscillation in the layer extrusion probably has a PT a bit longer than this, so probably more like ~15 - 20s.

Also, there would seem to be a second peak (red arrow) with a peak frequency ~= 0.33Hz, PT ~ 3s. This again would suggest the presence of a second mechanism that is producing an oscillation in the extruded layer width with a shorter periodic time.

So the analysis of this data set suggests that there are two mechanisms producing oscillations in the insulation layer thickness.

- A lower frequency mechanism, PT ~= 15 - 20s.
- A higher frequency mechanism, PT ~= 3s.

And, looking back at Fig 9, both of these modes of oscillation can be seen in the time series data.

Thus such frequency analysis opens up the possibility of using such analysis as a 'diagnostic' process that identifies the frequency characteristic of the mechanisms, within the extrusion process, responsible for the instability seen in the layer extrusions. With this knowledge potentially allowing the mechanisms themselves to be identified and, hopefully, improved.

In practical trials, on client production lines, the use of this 'Frequency Domain Feedback' approach has already resulted in the amplitude of the width variation in an extruded layer being reduced by a factor of four, resulting not only in material savings in the extrusion process, but also in a significant smoothing the critical insulation layer / inner screen interface.

Such frequency analysis can, of course, be applied to any of the Time Series data sets presented in this paper. For instance, applying this approach to the 'inner screen / core tube' diameter data - such as that presented in Fig 8 – obviously allows for the identification of the extrusion process mechanism(s) causing this variability.

However, it also opens up potential opportunities for the on-line monitoring of the degradation of the quality of this extrusion which, in conjunction with the contaminant detection capabilities also provided by UltraScreen, could present new ways to determine the optimum time to stop an extrusion production run.

SUMMARY

This paper has presented cable geometry measurement results and analyses that have only became available with the advent of fast-scanning, fine-grained measurement systems like the UltraScreen ultrasonic measurement system.

These results and analyses have raised the following key observations.

- That the thickness variations of the extruded cable layers, and the positions of the interfaces between them, exhibit significant variations over scale-lengths much shorter than a metre.
- That parameters evaluated from the base measurements, e.g. Concentricity, Ovality, Eccentricity, etc., also exhibit such short scale variations, and thus the cable 'cross-sections' use to evaluate them should be of the order of a few centimetres, not metres.
- That these observations are supported by data obtained from independent off-line measurement systems.
- That the 'Smoothness' of the insulation layer / inner screen interface can now be monitored and quantified.
- That the quality of the cable extrusion can now be monitored and quantified not only in terms of its time series characteristics, but also in terms of its frequency domain characteristics.
- That this frequency domain analysis provides a feedback mechanism by which extrusion quality can be controlled and improved.
- That such advanced analyses could provide on-line access to extrusion quality degradation information that could facilitate the informed identification of the optimum end point of a production run.

These results and analyses, underpinned by the fidelity of measurement provided by UltraScreen, are already being adopted by some of the most influential players in the cabling industry, and the ability of the techniques enabled by this new measurement technology has been accepted as having an important role to play both in material saving in the production of existing cables, and in the design and the production control required to produce, future, higher specification cables.

Thus the results presented in this paper give an initial insight into the standards of cable extrusion monitoring and production control that will perhaps be required to compete in the cable production market in the 21st century.