SUI GENERIS
INSPECTION CONSULTANTS

The Generation of Magnetic Fields in Oversized and Complex Geometries Using Flexible A.C. Cables

The Generation of Magnetic Fields in Oversized and Complex Geometries Using Flexible A.C. Cables

M. Sebastian (a), M. Ross (b)

a: Technical Director Sui Generis Inspection Consultants
b: Inspection Engineer at N-Sea Aberdeen

With special thanks to R. Wilson MinstNDT, FIAQP, LEP, Kim Hastings Director The Validation Centre and Mark Bentley of Oceanscan Aberdeen.

ARTICLE INFO

ARTICLE HISTORY:

Originators: M. Sebastian and M. Ross
1st October 2020

Reviewed: R. Wilson

Published:
Acadamia.edu
Insight - Journal BINDT

Keywords:

Magnetic Particle Inspection (MPI)
Subsea Inspection
Welded Node
KT-Node
Electromagnetic Flexible Cable
A.C. (Alternating Current)
UPRS (Underwater Photometer Radiometer System)
UFM (Underwater Flux Meter)
TWI (The Welding Institute)
Burmah Castrol Strip - Magnetic Flux indicator strip
PCN - Personal Certification in NDT
CSWIP Certification Scheme for Welding and Inspection Personnel

ABSTRACT

The Magnetic Particle Inspection (MPI) of critical structures in the subsea environment presents many challenges. This paper concentrates on the use of A.C. electromagnetic flexible cables on structural members that exceed operational limitations on diameter and complex geometry.

In order to appreciate the implications of this paper, a thorough analysis of existing subsea inspection methodologies, and their history, is included in order to provide essential technical context, identify problem areas, and their associated operational impact.

Viable alternative MPI techniques are explored based on a mathematical analysis of the induction of indirect magnetic fields using different configurations of flexible cable. Those systems are then empirically verified.

An overall exploration of MPI inspection ‘Best Practice’ is made and limitations in technical information and training are also detailed in the context of both the contractor and client liabilities.

This paper suggests new ways that multifaceted and branching surface breaking discontinuities may be inspected using electromagnetic flexible cables.

1. Introduction

Since the 1960s, government legislation has shaped the design and construction of offshore and subsea structures. Initially, Magnetic Particle Inspection (MPI) of subsea welded structures had proved itself to be a reliable and cost effective way of ensuring the continued safe use of those assets. Unfortunately in the late 1990s, due to the problems of ensuring technical competency, Subsea MPI began to fall out of favour. However, over the last ten years, a mixture of aging assets and rising costs, has forced engineers to reconsider this inspection medium; inevitably, this has led to the resurrection of many of the same problems that led to the demise of MPI as a subsea inspection technique. It is the intention of this technical paper to assist with information that may minimise these problematic areas found, and offer guidance on the future successful application of this inspection medium.

Historically speaking BS EN ISO 9934, as an international technical standard, has been used in an attempt to ensure the consistent application of the Magnetic Particle Inspection medium in the subsea environment. In order to achieve a Probability Of Detection (POD) approaching 100% for a relevant surface breaking discontinuity BS EN ISO 9934 Non-destructive testing - ***Magnetic particle testing - Part 1: General principles*** - 1 Section 8.1 General Requirements states that a flux density (B) of 1 Tesla or a tangential field strength (H) of 2 KA/m, at the point of inspection, is a basic requirement. Achieving this flux density in the subsea environment has proved to be problematic.

In the 1990s, electromagnetic prods fell from favour due to the likelihood of damaging the asset and permanent magnets were discounted due to poor migration of particles because of the direct field and slow rate of inspection. To date, only two viable means of indirectly inducing a useful magnetic flux in subsea structures are commonly available to the inspection engineer:

1. Electromagnetic Alternating Current Flexible Cables encircling the tubular steel member
2. Electromagnetic Direct Current Yoke

1.1 Electromagnetic Alternating Current (A.C.) Flexible Cables (Encircling):

Since the 1980s, the preferred method for providing an adequate magnetic field for subsea inspection of structural members has been through the use of Electromagnetic A.C. Flexible Cables. Originally these cables were supplied via the OIS Underwater Technology Systems II oil filled underwater transformer delivering up to 1000 Amps. Currently this unit is manufactured and supplied by The Validation Centre (TVC) Ltd as the ASAM System III. The modified system provides up to 1500 Amps and is typically supplied with a **12.5m A.C. Flexible cable**. This length of flexible cable was established by the manufacturer as the optimum for the creation of a magnetic field as a balance between resistance and utility. However, over the years, a certain amount of customisation of older units has occurred and measured cable lengths do vary.

FIG 1: ASAM SYSTEM III

1.2 Problems and limitations in the use of A.C. Flexible cables on structural members: Diameter

Historical context: The British Institute of Welding Engineers was created in 1923. In 1968 that august body became the Welding Institute based in Cambridge England and oversaw the creation and implementation of the CSWIP (Certification Scheme for Welding and Inspection Personnel) system.

It is the CSWIP 3.1u, 3.2u and 3.4u qualification that has, since the 1980s, been the industry standard for setting the competency of personnel working in Subsea Inspection. Indeed, it was through the publication and dissemination of its training courses, technical manuals and recertification that TWI (The Welding Institute) has established and defined inspection industry standards and 'best-practice'. The CSWIP / TWI inspection manual includes a section on the use of Magnetic Particle Inspection in the subsea environment and practical competency is assessed through the CSWIP 3.2u exam.

It is a fact, therefore, that TWI has defined how subsea Magnetic Particle Inspection is done and who is considered competent to complete it. **As we will see, this esteemed position has a direct impact on how 'oversize and complex' geometries are typically accommodated and what limitations have existed, to date, within the industry**.

In the April 2006 edition, the instructions for the application of Close Wrapped Coil appeared in **section 6.4.2**, which states that "**3 x turns of the electromagnetic cable"** around the member under test **"is a minimum requirement" (see fig. 2)**.

The implications of that statement are physically significant. Assuming that the ASAM III Subsea Pot can be brought within a metre of the work site, we will inevitably lose an average of 1m of the cable from the pot to the joint and from the joint to the pot resulting in the overall approximate loss of 2m of our electrical flexible cable before we have even wrapped the coils onto the member.

Experience has shown that only 10.5m of cable is typically available to create the required 3 x cable wraps around the circumference of the member. This implies that the **maximum diameter** of member, that the coils can be **easily** (physically) used on, is **no greater than 1.1m**. If we assume no loss due to rigging only a diameter of 1.3m is theoretically (physically) possible.

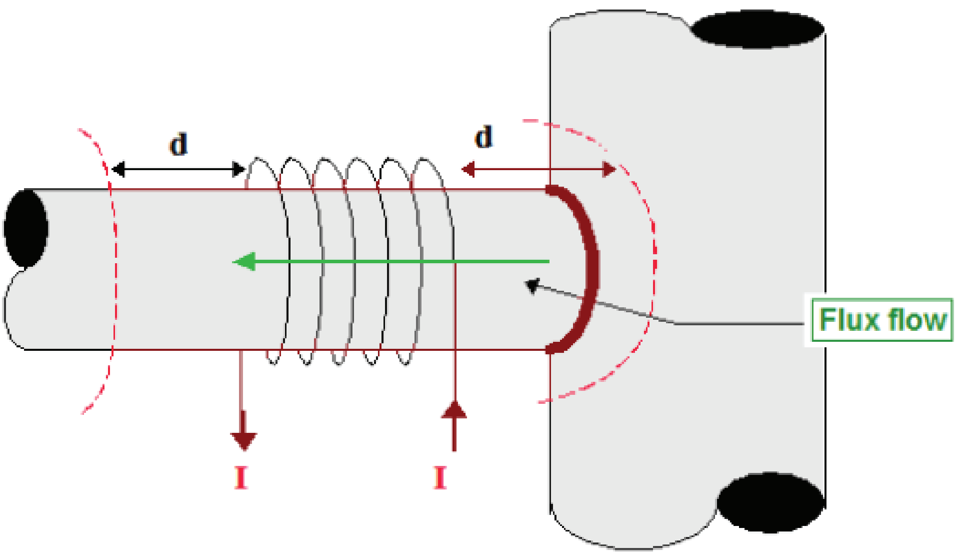

Figure 14.28

Close Wrapped Coil

The current requirement for this technique is determined by the formula: -

$$I_{peak}\,(ac) = \frac{16 \times r}{N}$$

Where I_{peak} = The peak current value (AC)

r = The radius of the coil (mm)

N = Number of turns in the coil (minimum 3)

16 = Constant

FIG 2: TWI / CSWIP 3.4u (3.2u) manual section 6.4.2

Figure 2. above, taken from the CSWIP TWI Inspection manual, specifically states that a minimum of 3 x turns around the tubular member are required.

Please note Close Wrapped Coil Formula above (16 x r over N) - we will return to this later in our paper.

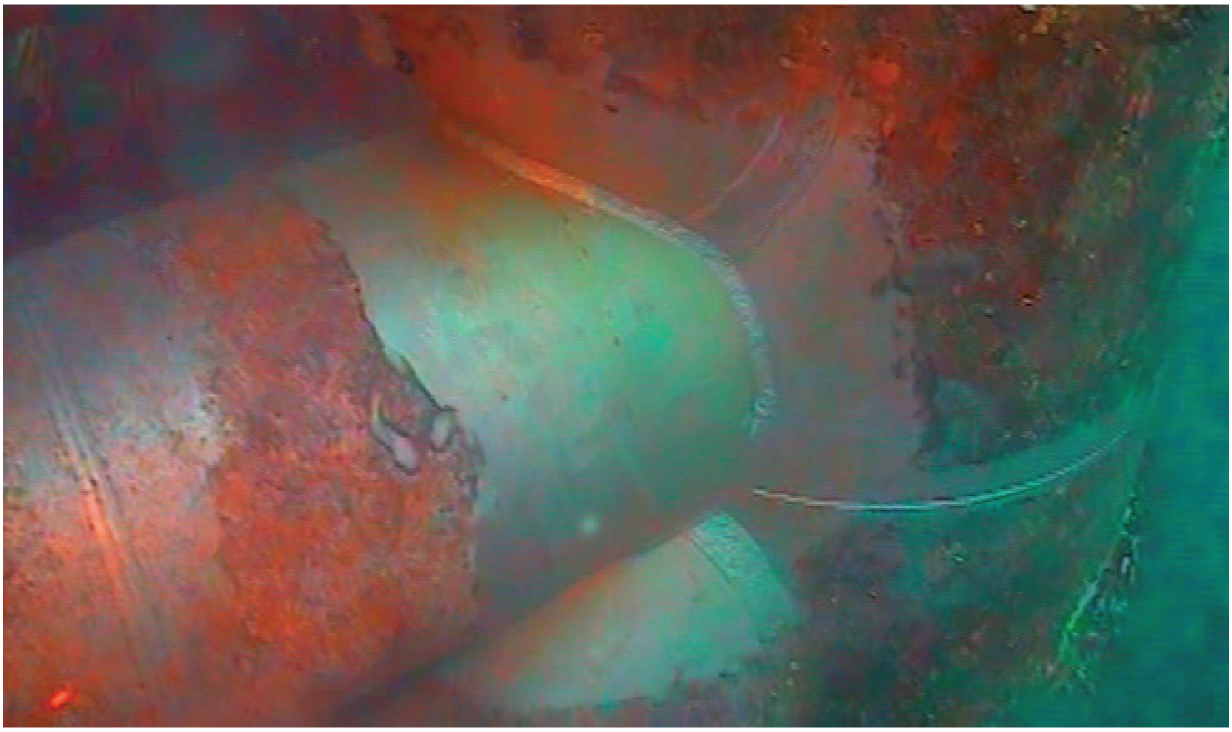

FIG 3: Horizontal Member to Jacket Leg forming a KT Connection on a typical offshore structure.

1.3 Problems and limitations in the use of A.C. Flexible cables on structural members: Geometry

The 12.5m Electromagnetic Flexible cable has an overall diameter of 21mm and it is the job of the diver to manually position that cable as close as practicably possible to the area under magnetic particle testing; this usually involves using several horseshoe magnets and complicated rigging in order to hold the coils in position. Typically, the three wraps of flexible coil together need to follow the line of the structural member's attachment weld, which further increases the practical length under test beyond the member circumference. As most structural 'Hot Spots' include node weld connections ('KT' Nodes) their weld geometry is inherently complex and further decreases the maximum of member diameter that can be tested with this technique.

However, this is not the only problem; it is understood that the magnetic field induced within the 13mm diameter copper wire decreases by the ratio of the inverse square law, this makes it vital to position the coils as close to the test area as possible. This is a time consuming and difficult job to perform underwater and, as with most things, comes quicker with practice.

When the electromagnetic coils are closely wrapped around a ferrous steel member it is possible for the magnetic field to increase in strength according to Faraday's law (flux is directly proportional to the number of turns in a coil); thus theoretically extending the radius of the useful field. This Superposition provides a one directional magnetic field perpendicular to the line of the coil. This means that only discontinuities whose aspects lay longitudinal to the weld (usual test subject) will be visible. Transverse discontinuities that lay transverse to the weld axis and parallel to the coils magnetic flux lines are less likely to produce strong leakage fields from discontinuities that would or could be present and may not be detected by the naked eye leading to another significant limitation in this MPI technique related to geometry.

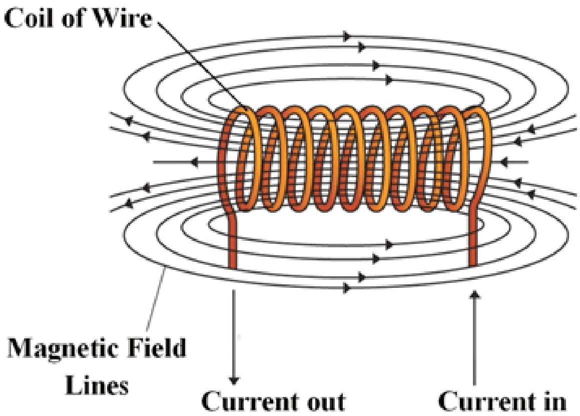

FIG 4: Magnetic field created by an electrical current running through a coil of copper wire.

1.4 Problems and limitations in the use of A.C. Flexible cables on structural members: Theoretical

The application of BS EN ISO 9934 in the context of a subsea industry, which is constantly changing, has long been a source of misunderstanding and has inevitably led to a lot of wasted time and money.

For example, when carrying out florescent MPI Inspection, BS EN ISO 9934-3 Section 5.3 states that the maximum ambient light allowed within 400mm of the test area must not exceed 20 lux, as does BS EN ISO 3059. From an operational point of view, this limitation implies that MPI could only be completed during the darkest hours of night when diving within the air range of 30 meters. As advances in fluorescent inks and UV-A Light sources have been made over the last ten years, this restriction has been largely unofficially abandoned but, due to conflicting information and advice, confusion continues, to the cost of our clients.

Likewise, as previously mentioned, the official TWI Manual for Subsea Inspection includes an unreferenced formula for calculating the required Peak Amperage for the application of the Close Cable MPI technique.

Peak A.C Current = 16 x member radius divided by the number of cable turns

Inspection engineers attempting to plan future inspection campaigns or those engaged by the client to provide quality assurance inevitably find this formula of little use. For example, please consider a 1m diameter horizontal member. This would imply a radius of 500mm. According to the formula provided, in order to achieve a field sufficient to inspect with Magnetic Particle Inspection (presumably 1 Tesla) three wraps of the electromagnetic coil around the member would require 2666 amps. Unfortunately, the maximum amperage output of the ASAM III unit is 1500amps A.C. This means that if the TWI formula were correct it would have been impossible to inspect correctly most of the subsea jackets in the North Sea.

It is evident, therefore, that there are limitations in the available general technical information relevant to the application of subsea MPI. It is the intention of this paper to highlight and address those limitations.

1.5 Questions addressed in this paper:

In light of the problems and obvious limitations of the A.C. Electromagnetic Flexible Cables in regard to diameter, geometry and theoretical guidance, this paper addressed the following questions:

1.5.1. How can A.C Electromagnetic Flexible Cables be quickly and efficiently used to provide a flux density in access of 1 Tesla in structural members, which exceed operational diameter and geometry limitations?

1.5.2. How can A.C. Electromagnetic Flexible Cables be used to efficiently provide an acceptable magnetic field and associated POD on transverse, multifaceted and branching discontinuities?

2. Materials and Methods

During an offshore campaign in the late summer of 2020, in order to comply with client requirements and time constraints, it was necessary to find a rapid solution to the two questions listed above. Therefore, a mixture of empirical and exploratory experimentation was completed in the workshop environment. Theoretical validation was then used to detail findings. Ultimately, the suggested systems were implemented in the field and extensively proved empirically.

2.1 Available equipment

Three ASAM III MPI units were available to the team during the campaign. Field measurements were made using one of three UPRS (combined light and gauss meter) units, which are supplied with a built in Gauss Meter that reads from zero to 19.999 Tesla.

These measurements were supplemented by the use of Chemetall Suretest type 1 Flux Strips. Otherwise known as **'Burmah Castrol Strips'**, they consist of a body of 50mm x 12mm and provide a form of artificial discontinuity that confirms field direction and, by implication of the flux leakage relative to discontinuity, an adequate flux (B) density in order to confirm theoretical POD. These strips, when in intimate contact with the test surface, prove the existence of an induced field exists across the surface of the test area; however, it should be noted that field strength (H) cannot be reliably measured with these strips due to the fact that encircling coil, yoke magnetisation, adjacent cable and permanent magnets provide a primary magnetic field in air which may or may not penetrate into the test subject.

A fluorescent magnetic ink was used during testing and operations. Mi-Glow UW 12 (which replaced Mi-Glow UW 528) was used due to its previous success in 'Daylight' conditions (up to 720 lux ambient light - in laboratory conditions according to Ken Woolley et al in their 2015 paper entitled ***'A fresh initiative on the use of daylight magnetic particle inspection for the inspection of underwater steel structures'***).

The inspection team had available a range of test specimens of nodal joint configurations brought on board the vessel for ultrasonic technique validation and verification. These test samples were used to verify the possible MPI technique options available to the team in 'Workshop' conditions.

2.2 Inspection Personnel

Physical MPI was completed Subsea by Diver/Inspectors qualified to CSWIP 3.2u and with regular experience of the inspection medium, under the supervision of Inspection Controllers holding similar qualifications in addition to the CSWIP 3.4u certificate and topsides qualification and experience.

3. Results

When it was realised that it would not be possible to use the 'encircling close coils' technique due to the geometry of the test subject, use of the 'Kettle Element' technique was considered as detailed below.

3.1 'Kettle Element'

TWI Subsea Inspection Manual from April 2006 details the **Parallel Loop** Technique of laying the A.C. Electromagnetic Flexible Cables on page 345 - fig 14.29. Historically this solution has been called the **'Kettle Element'** system. As the system provides a transverse field between two sides of two contiguous loops and depends on the distance between those two discrete loops, it is defined by the following mathematical formula:

$$I = 30 \times d$$

A.C Current (Peak) = 30 x d (Where 'd' is the distance between loop 1 and 2)

As stated by TWI manual the area under test should, ideally, be located **between** these two loops (distance 'd').

According to the TWI formula, given that the ASAM III unit only produced an output amperage of approximately 1000 amps, this would have restricted us to a test area of only 33mm - it was obvious that applying the Kettle Element technique was fundamentally flawed for practical inspection due to time constraints and adequate field of view.

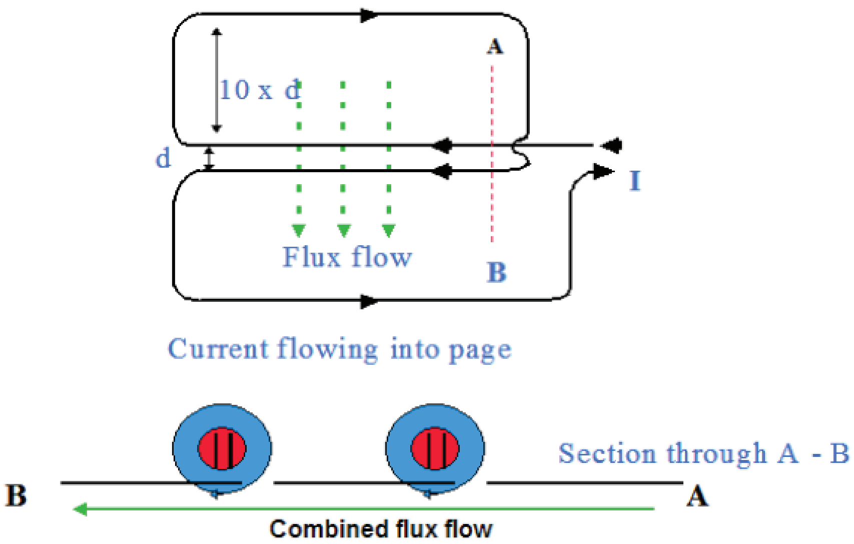

Figure 14.29

Parallel Loops

This produces a transverse field between the two sides of the loop. The loop has to be positioned so that the current in the two sides of it is moving in the same direction or else the magnetic fields will tend to cancel instead of reinforce. Furthermore the return cables not forming the parallel loops must be a minimum of 10d away from the inspection area as shown in Figure 14.29. The direction of the field may be ascertained by applying the "*right hand rule*". The required current may be found by applying the formula: -

I_{peak} (ac) = 30 x d

FIG 5: Parallel Loops as described in TWI Subsea Inspection Manual April 2006.

3.1.2. 'Kettle Element' inspection competency

Whilst it is true that the Parallel Loops (Kettle Element) technique has been included in the TWI Inspection manual for many years, it has not been a part of the CSWIP 3.2u practical exam and as the course is entirely focused on preparation for that exam, due to time constraints, it is rare that the 'Kettle Element' technique is physically practiced. More importantly, competency is not tested in the CSWIP 3.2u exam. For the above two reasons the use of the TWI Parallel loop technique was discounted as a viable alternative.

3,2 Quadrant Coil Bundle:

It was evident that the TWI Subsea Inspection manual offered no useful advice for the application of A.C Electromagnetic Flexible Cables in situations that exceeded operational restrictions on circumference and geometry. The team realised that, in order to provide our client with the results they required, we needed to find a physical solution that could also be justified theoretically.

It was noted that a coil of MPI cable continued to generate a magnetic field despite being separated from a ferromagnetic core. The following system was considered:

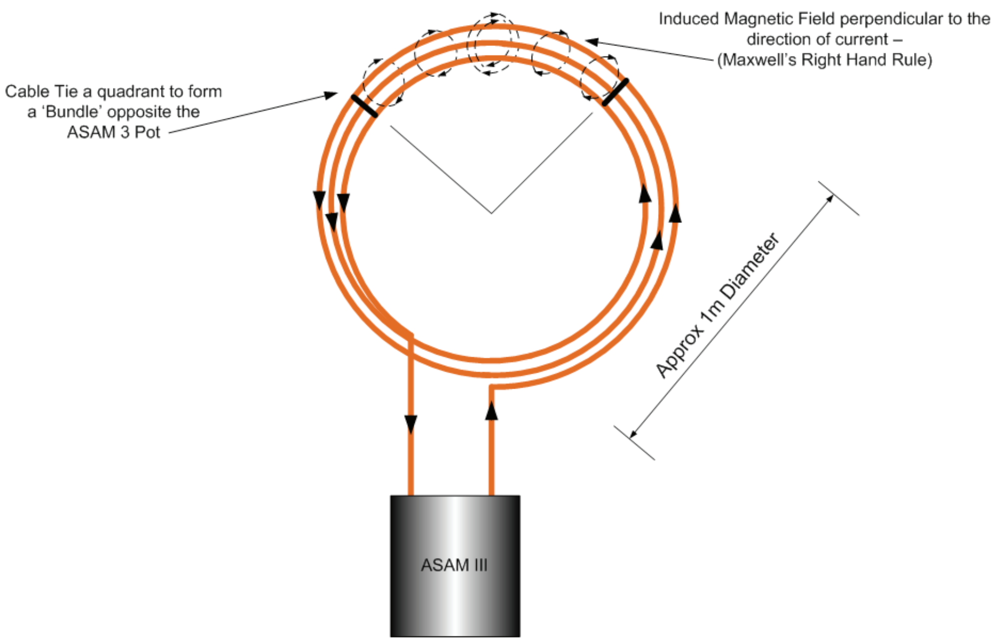

FIG 6: The Quadrant System of A.C. Flexible Coil DESIGN.

It was noted that **BS EN ISO 9934-1 Annex A7** (8.3.2.6 and figure 11) '***Coil Formed by Flexible Cable***' offered guidance on the correct mathematical formula for a A.C. coil formed by flexible cable. ***See Addendum 8.1.***

$$I = 3H\,[10 + (Y^2 / 40)]$$

Where I = (RMS) Value of the current in amperes

Where H = Tangential Field Strength in Kilo amperes per metre

Where Y = Spacing **between** adjacent windings (turns) in the coil in millimetres

This formula is a way for the Inspection Engineer, or suitably qualified inspection technician (PCN Level 2 or equivalent), to predict Tangential Field Strength based on A.C Current within a wire. The formula is only limited by the distance **between** coil turns. It is important to note that the formula is **not multiplied by the number of turns** nor by the diameter of the coil. It, therefore, appears to be a calculation of the magnetic force encircling a wire.

The formula suggested that, provided that the distance between our turns did not exceed 5mm, our coil should contain 1 Tesla at a Peak current of approximately 90 amps. With our capacity of approximately 1000 amps it was possible to increase magnetic field by a factor of 11 and, as we later proved, the radius magnetic field.

A Quadrant Electromagnetic Coil Bundle (3 x loops) was made in the workshop. The generated field appeared to be independent of local changes in permeability and using Burmah Castrol Flux Indicator strips it was established that the field appeared to be present in the air around the coil rather than within the base material. Direction of field was perpendicular to the line of the coil.

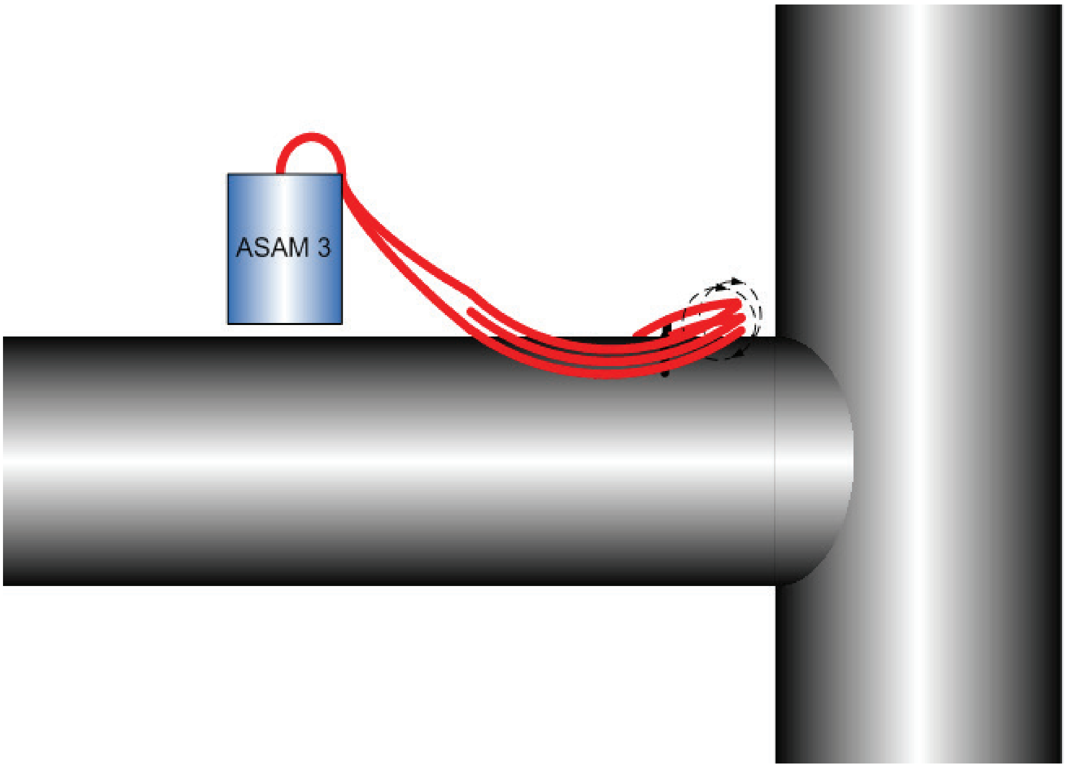

FIG 7: The Quadrant System of A.C. Flexible Coil deployment.

Due to the location of the surface breaking defects we were trying to investigate, we were concerned to make some kind of a prediction as to the distance (radius) that the induced magnetic field would extend beyond the wire. Theoretical calculations were made based on the formula below.

3.2.1 Field Distance (Radius) Single Wire - See Addendum 8.2

$$r = \frac{\mu 0 \cdot I}{B \cdot 2\pi}$$

Where $\mu 0 = 4\pi \cdot 10^{-7} \cdot T_{m/A}$

I = Current Peak

B = 1 Tesla

$\pi = 3.142$

FIG 8: Formula for radius of circular field around a single cable (from Ampere's Law).

This ***Field Distance (Radius) Single Wire*** formula above suggested that the permeability of air (μ0) multiplied by our peak current (1000 Amps) could be divided by the target flux density (1 Tesla)and again multiplied by twice the value of Pi (3.142). This would mean that at our peak current of 1000 amperes we would have an extended **magnetic flux of 1 Tesla at about 399mm from the cable**.

Testing with both the gauss meters and burmah castrol strips in the workshop environment on deck seemed to confirm that this was indeed the case.

Unfortunately, by this time, due to operational constraints we were running out of time. Using the Quadrant Bundle system with a coherent tangential field we would need to place the coil bundle at right angles to each test area due to the fact that our intended inspection area included previously reported multifaceted branching surface breaking discontinuities. This would cost us diving time we didn't have. The decision was made to try to 'randomise' the induced field.

3,3 Compressed Flexible Cable Bundle:

As nearly all systems of '**Indirect Magnetisation**' induce a magnetic field **first** within the air, it is therefore necessary to empirically prove each test surface in order to ensure that sufficient flux density has been induced and is present in the test body itself in order to confirm that it would cause flux leakage to occur in the event of a discontinuity.

Given this fact, a quadrant bundle was compressed so that the entire coil was made into a close coil bundle. **It was postulated that this configuration might allow us to provide an oblique magnetic field that might reveal discontinuities not necessarily parallel to the line of the electromagnetic coils** and not limited by the normal homogeneous field that exists perpendicular to those cables.

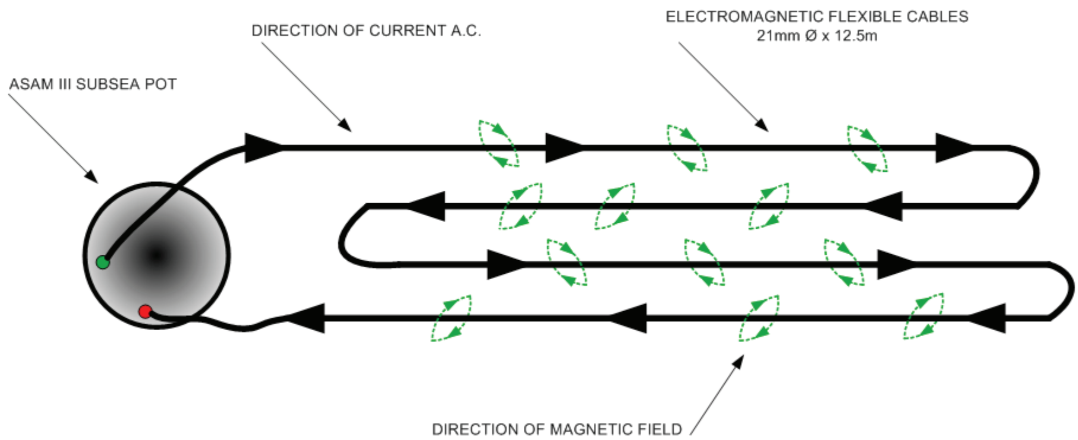

FIG 9: Compressed Flexible Cable Bundle.

It had been previously observed that our output current was reduced in proportion to the amount of times the flexible cable was coiled around a member. We deduced that this was due to the increase in electromagnetic impedance caused by the proximity of the coils and the induced counter current. It was therefore postulated, from these observations and contrary to common assumption, that these changes in impedance would not seriously reduce the **density** of the induced magnetic flux but would, in fact, alter their direction in accordance with Ampere's law.

At this point we referred to BS EN ISO 9934-1 A.7 formula for '***Coil Formed by Flexible Cable***' and confirmed that flux density appears to be a product of primary current and is not affected by the number of adjacent coils.

It was empirically observed during testing that reductions in magnetic flux due to distance follow the inverse square law as is supported by the formula for field generated in a single wire (Ampere's Law).

Prior to deployment subsea this configuration of coils was tested with both the UPRS Gauss meter and Burmah Castrol Strips.

It was evident that the Compressed Coil Bundle did not 'cancel out' magnetic field but rather redirected it. The equations suggested, and testing confirmed, that the Compressed Coil Bundle was indeed providing a magnetic field over 1 Tesla to a radius of approximately 300mm. However, field direction was not definitively confirmed although discontinuities transverse and oblique to normal were confirmed.

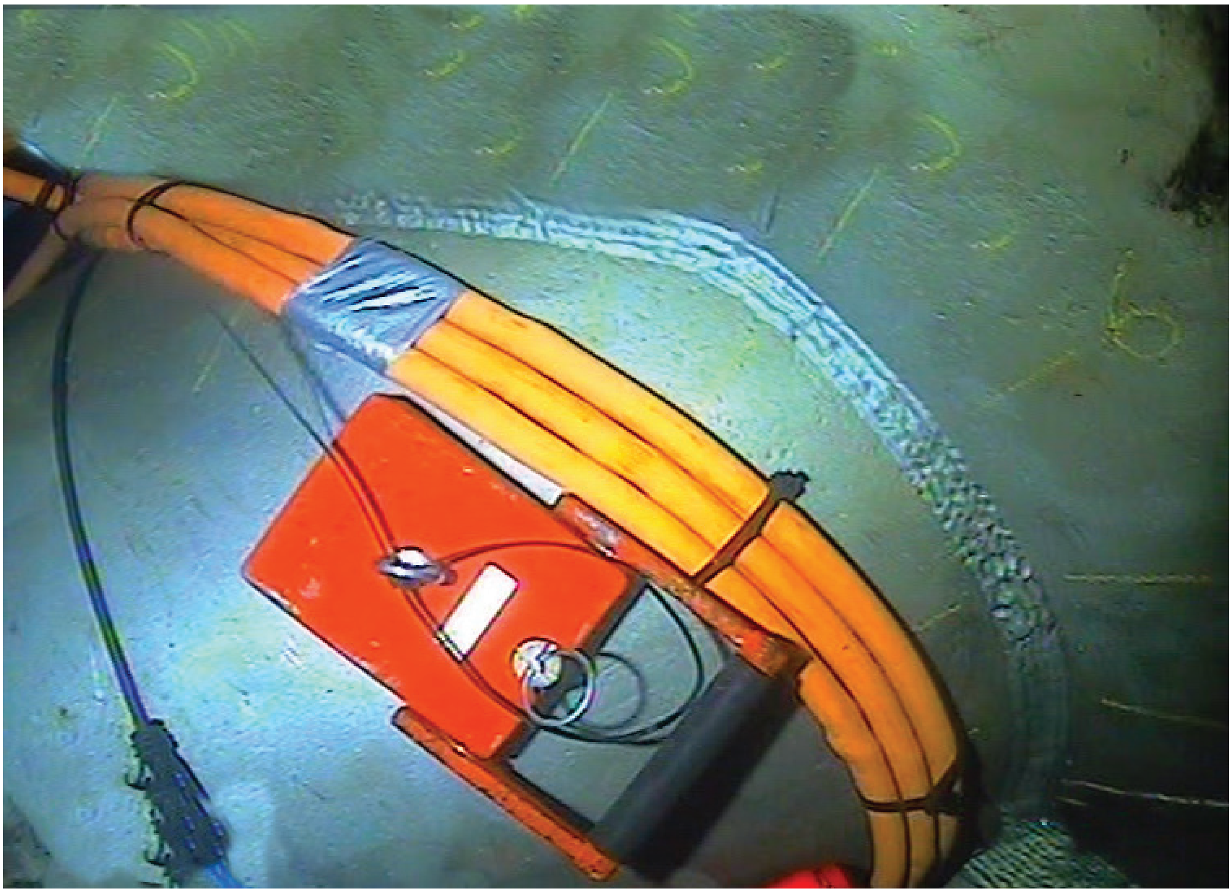

FIG 10: Compressed Flexible Cable Bundle deployed over horizontal structural member.

3.3.1 Deployment subsea

After deployment of the Compressed Flexible Cable Bundle to the subsea work area, the following quality assurance checks were completed and were repeated on completion of the test:

1. Magnetic Field was confirmed at a position beyond the expected test area using the Burmah Castrol Strips in line with expected discontinuity ensuring that a clean strip was used and intimate contact with test surface was confirmed by the diver/Inspector. All three lines were clearly visible.

2. UVA-Light was confirmed to be > 1000 μW/cm² at 400mm from test subject.

3. Ambient Light was confirmed to be 70 Lux.

4. Mi-Glow 12 Ink was maintained agitated prior to and during inspection.

3,3.2 Results for Compressed Flexible Cable Bundle:

In order to prove the validity of the compressed flexible cable bundle it was necessary to confirm a known discontinuity branching from an already known through-wall crack. The discontinuity was indeed confirmed. A known branch crack, perpendicular to the line of the crack, was also confirmed without the need to reconfigure the cables.

Having deployed the ***Compressed Flexible Cable Bundle*** parallel to expected line of the discontinuity it was noted that the main known crack was clearly showing signs of significant flux leakage. It was also observed that the branching crack at 90º to the main discontinuity was also visible with no sign of a drop in flux leakage (as would normally be expected).

As soon as the inspection diver applied the Mi-Glow 12 ink to the test area the expected crack, in its full entirety, was immediately obvious including the section running 90º away from the main line of the crack. In order to confirm that we had not missed any other areas of propagation the MPI electromagnetic cables were repositioned perpendicular to the initial set up. This repositioning of the magnetic field did not reveal any further crack propagation missed by the initial setup.

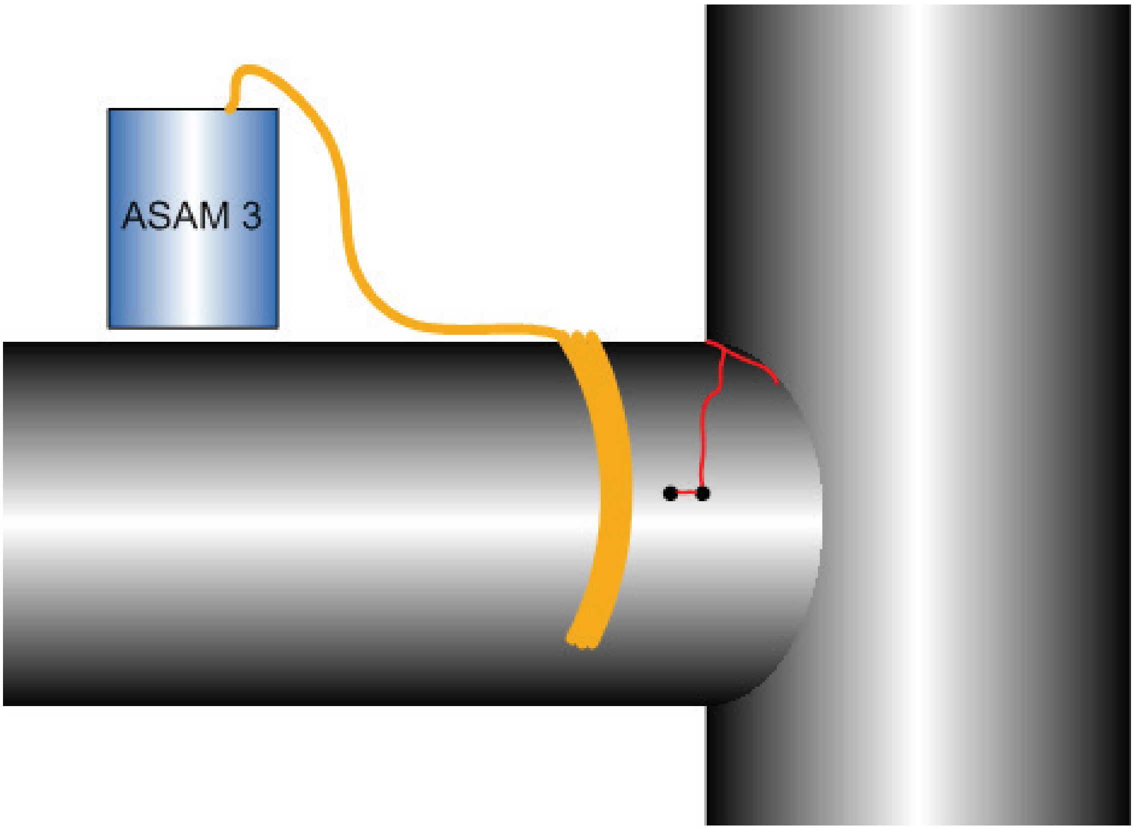

FIG 11: Discontinuities revealed at angles approaching 90 degrees.

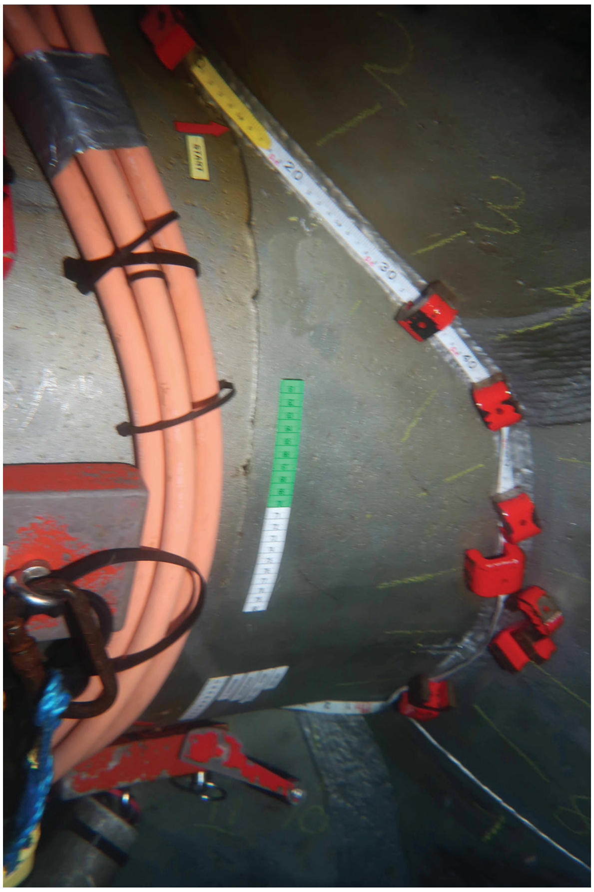

FIG 12: General Arrangement of Flexible Bundle relative to discontinuity.

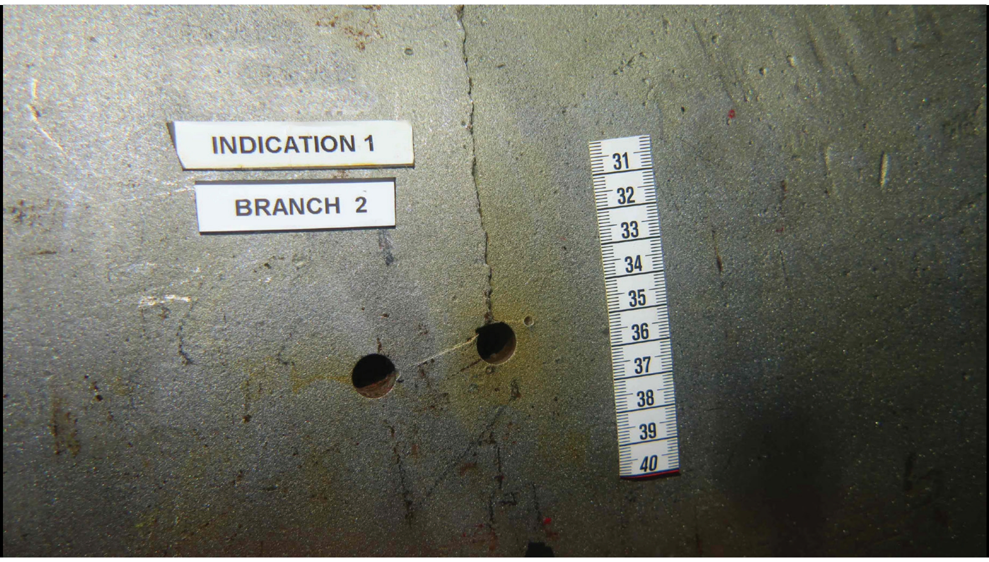

FIG 13: Close up showing vertical crack and horizontal transverse branch: ambient light.

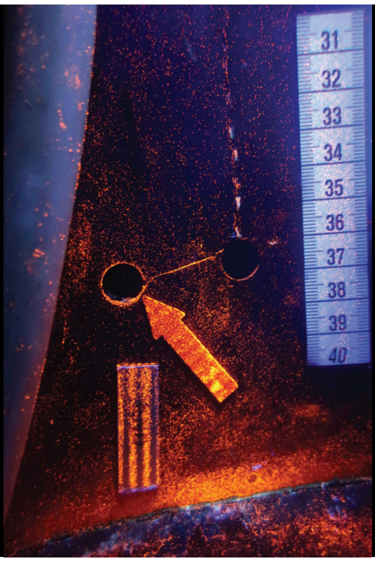

FIG 14: Close up showing vertical crack and horizontal transverse branch: UV-A light.

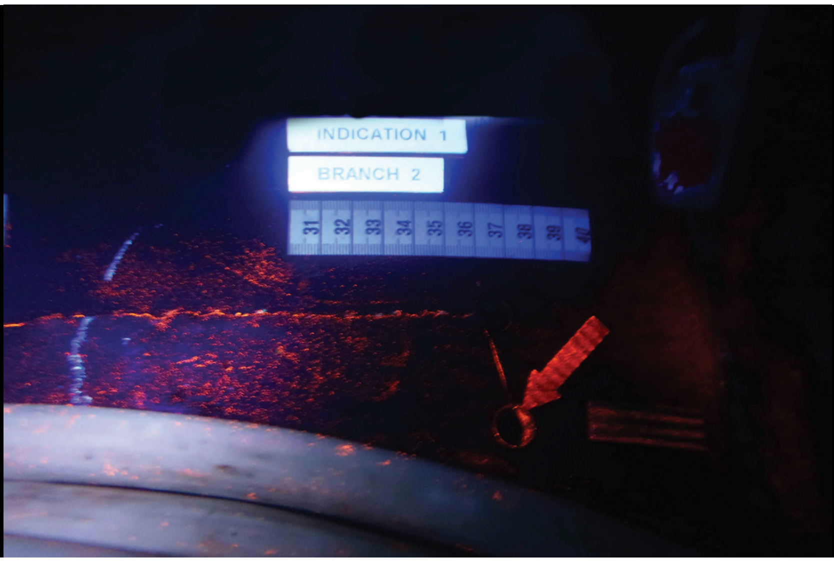

FIG 15: Detail of indication at 90 degrees with view of cable in lower screen.

4. Discussion

4.1 Flexible Cable Bundle Effectiveness

Due to operational constraints it was not possible to verify, with any accuracy, specific changes to the direction of magnetic flux caused by the compression of the cable coil. That being said, it was evident that we were getting sufficient field to locate reportable discontinuities.

The ***Compressed Flexible Cable Bundle*** appeared to provide the widest possible cover without repositioning of the cables. However the Quadrant Flexible Cable Bundle would provide a more homogeneous magnetic field and theoretically a greater radius. Further investigation is required to confirm the extent of that radius.

4.2 Magnetic Field Verification

Further investigation is required if we are to confirm the effect of compressing a cable coil. A series of pocket compasses might be placed along the line of the coil bundle in order to check the direction of flux and a Gauss meter to confirm flux density (Tesla). Ampere's Law does suggest that this form of compression might cause areas of the magnetic field to rotate - this needs to be confirmed..

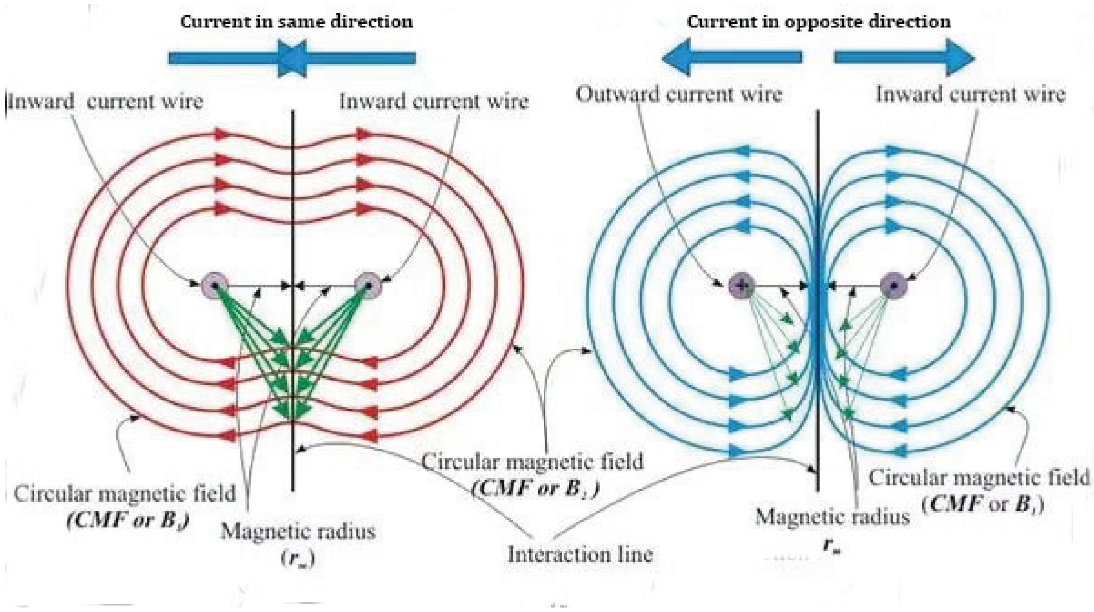

FIG 16: Forces between two wires containing opposing current showing flux compression.

Within the Subsea Inspection Industry there has been historically an over reliance on the Burmah Castrol strip as a verification of magnetic field with the assumption that they confirm flux density (1 Tesla) and/or Field Strength - this is not generally the case. The Flux Indicator Strip (Burmah Castrol Strip) must be clean (old ink causes false positive readings) and must be in direct intimate contact with the test surface in order to confirm flux is present and in what direction. Therefore for subsea inspection, no measurement of magnetic force (H) can be assumed. It must also be pointed out that there is often a difference in contrast between the strip and the test object itself so it would be unwise to rely solely on the Burmah Castrol strip to confirm visual quality assurance.

During the investigation, magnetic flux indicators (Burmah Castrol strips) type 1 and type G were used as artificial discontinuities in order to demonstrate the possible direction of field and the POD for reportable discontinuities.

4.3 Electromagnetic Yoke

During this investigation, the ASAM III DC Yokes were checked on the surface and both were confirmed to have a magnetic force (H) sufficient to lift an 18 kg weight. However, on deployment subsea, the Yokes did not provide a field sufficient to show three clear lines on the Burmah Castrol Strip (B). It was for this reason that their use was discounted.

4.4 MPI Ink Viewing Conditions

Mi-Glow 12 was the fluorescent ink chosen for this project, which has superseded Mi-Glow 528 UW. With a particulate less than 12 μm it provided good adherence to all reportable discontinuities. The Ink powder was mixed according to manufacturers instructions at 15g of powder to 1litre of water. This mix provided a solid content of approximately 2. We can confirm that good results were achieved with ambient light >200 lux suggesting that 720 lux might be attainable.

4.5 ASAM III Set-Up

As long as the surface control unit of the ASAM III has an electrical supply greater than 220 Volts and 30 Amps of current it should provide 1500 Amps to the flexible cable with no coils in place.

As the ASAM III unit only has a 5 Volt output any increase in resistance will exponentially reduce the available current. In particular, any extension to the length of the flexible cables will cause an increase in resistance. Regular maintenance of the unit is critical, as is a confirmation of the power delivered to the surface control unit. It is possible to reconfigure this unit to accept 200 - 250 Volt A.C. Single phase or 380 - 440 Volts A.C 3 x Phase.

The manufacturer of the ASAM III (The Validation Centre) will be relaunching their product some time in 2021. It will be possible to obtain a retro-fit system to provide an A.C. Yoke and an LED UV torch to replace the old bulbs. Also they will be relaunching the UPRS Light/Gauss meter.

4.6 MPI Competency

A great range of technical competency was noted within our inspection team. To complete MPI inspection successfully a level of genuine interest in the medium is vital as is a chance to practice and experiment without the stress of operational limitations. It is logical therefore, that those divers who demonstrate these qualities should be valued and encouraged. It is evident that compulsory re-certification at annual or five year intervals has not, of itself, contributed to technical competence. On-the-job training and practice has proved much more effective in ensuring speedy and accurate results.

4.6.1 MPI Competency - CSWIP 3.2u Vs. 3.4u

Relevant to this investigation, it is important to note that the CSWIP 3.4u ***Inspection Controller*** qualification is not proof, in itself, of practical inspection competency as described in BS EN ISO 9712: 2012 '***Non-destructive testing. Qualification and Certification of NDT Personnel***'. Unfortunately, those holding the CSWIP 3.4u qualification are often expected to act as technical authorities over disciplines within which they hold no practical experience or qualification. Conversely, those holding the CSWIP 3.2u, as a practical competency, are often excluded from the inspection QA/QC process. This 'exam based', as opposed to 'competency based', approach has a cost and time implication that should be of a profound concern to the client. From a legal point of view, a CSWIP 3.4u is not qualified to sign off on an MPI inspection report (without a CSWIP MPI level 2 or its equivalent).

5. Conclusion

This paper was intended to provide the industry with a basis for discussion and further investigation in the hope of improving the reliability and efficiency of subsea magnetic particle inspection in general and in the use of A.C. electromagnetic flexible cables in particular.

It is now clear that using a bundle of three cables, either as a quadrant or as a compressed bundle offers a way for inspection engineers to successfully overcome the challenges of large diameter members or those members (KT for example), which demonstrate complex geometry.

With regard to multifaceted or branching cracks, the compressed cable bundle system may offer a wider field of inspection and savings in operational time - as proved to be true during our project but in order for this system to be reliably adopted there will need to be further investigation in order to confirm relevent technical details.

With the advent of the new ASAM III and the ability to use an A.C. Yoke, many of these problems may disappear. The new UPRS system from TVC will improve our ability to accurately measure magnetic field.

With regard to training and competency, it is important to note that the CSWIP system was created during an era when the UK was an industrial nation with a strong apprenticeship system. It would be a mistake to underestimate the vital contribution that the Welding Institute has made in creating and maintaining standards within the inspection and welding industry. In many ways, as Europe moves into an epoch that might be called 'post-industrial', it must be recognised that the challenges that face the inspection industry are not the responsibility of one group of people or one institution. Without the apprenticeship system, vulnerabilities within the industry are inevitably brought into focus. However, without facing those vulnerabilities the subsea inspection industry cannot provide its clients with reliable and cost effective inspection solutions.

6. Acknowledgements

I would just like to thank Mr Kim Hastings of the The Validation Centre (TVC) for his patience and his enthusiasm in offering our team advice and access to his technical knowledge of the ASAM III systems.

I would also like to thank Mr Ray Wilson for it was upon his training that so many of us based our careers. It was his dedication to top quality inspection that inspired everyone of the Subsea Inspection team.

Also I should thank the following companies for their time and patience in the creation of this paper:

- Mr Mark Bentley of Oceanscan Aberdeen
- Chemetall Aerospace Technologies
- Mr Bruce Banfield, Ken Woolley, Tim Woolley for their paper on the use of 'Daylight' MPI ink.

7. References

- TWI Tuition Notes for 3.4u Course (DIS 4)
- TWI Tuition Notes for 3.2u Course (DIS 2)
- BS 6072: 1981. Magnetic Flaw Detection
- BSI. (2001). BS EN ISO 9934-1:2001. Non-destructive testing. Magnetic particle testing. Part 1 - 2 and 3
- BSI. (2005). BS EN 1330-7:2005. Non-destructive testing Terminology. Terms used in magnetic particle testing
- BSI. (2012). BS EN ISO 3059:2012. Non-destructive testing. Penetrant testing and magnetic particle testing. Viewing conditions.
- Technical Paper: '***A fresh initiative on the use of daylight magnetic particle inspection for the inspection of underwater steel structures***' - Bruce Banfield et al.
- Chemetall Aerospace Technologies - Technical Information A001 - Suretest Flux Strips.

8. Addenda

8.1 BS ISO 9934-1 A.7 Coil Flexible Cable formula

$$I = 3H\,[10 + (Y^2 / 40)]$$

Where I = rms. Value of the current in amperes
Where H = Tangential Field Strength in Kilo amperes per metre
Where Y = Spacing between adjacent windings in the coil in millimetres

Example:
Consider Y = 5mm. $5^2 = 25$ which implies 25 /40 and gives 0.625 and then add 10 resulting in 10.625

H = 2 (Kilo Amps per metre) 3 x 2 = 6

Multiply 6 x 10.625 = 63.75 amps RMS

Divide 63.75 by 0.707 to find peak value -- this results in 90.17 Ams peak

Thus: Coils wrapped not to exceed 5mm gap (bundled) will yield 2 KA/m at a peak A.C. Current of approximately 90 amps.

Note: This formula is not predicated on the number of coils.

8.2 Field Distance (Radius) Single Wire formula

Field Distance (Radius) Single Wire

$$r = \frac{\mu 0 \cdot I}{B \cdot 2\pi}$$

Where $\mu 0 = 4\,\pi \cdot 10^{-7} \cdot T_{m/A}$

Where 10^{-7} = 0.0000001
Where π = 3.142 x 4 = 12.57
Where T m/A = 2000
Where I = 1000 Amps.

Implies: $4\,\pi \times 10^{-7} \times T_{m/A}$ = 0.002513

Thus 0.002513 x 1000= 2.513

B = 1 x 2π = 6.283

This allows us to divide 2.513 by 6.283 and gives us 0.399 Metres

Thus: at a peak A.C current output of 1000 amps the field radius around the cable would be 399mm..