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Ultrasonic Multi-Skip Inspection at Clamped Saddle Supports

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Abstract
The ultrasonic Multi-Skip inspection technique has made a modest entry in the world of advanced ultrasonic inspection methods. As an intermediate-range inspection technique, it has proven particularly useful for the inspection of pipes at clamped saddle support locations. In order to shed some light on its capabilities and limitations, this paper is presenting some results of Multi-Skip inspections done on 36” and 48” diameter pipe of 34 mm as well as 9.5 mm wall thickness. The sensitivity and the accuracy of the technique are demonstrated using field measurement results and the feasible application range is discussed. With its high sensitivity to local wall loss, the Multi-Skip inspection technique appears to be a welcome addition to the currently available Guided-Wave and CHIME inspection methods for inaccessible locations.

Keywords: Multi-Skip, ultrasonic inspection, pipe support, inaccessible location

1. Introduction

Pipe supports may have different forms and dimensions. In all cases, however, at least the 6 o’clock pipe position is resting on the support and is as such inaccessible for conventional (wall thickness) inspection techniques. The most common type of support is the simple sleeper support: the pipe is resting on a steel bar or an H-profile, and only a small part of the pipe is touching the support, at the 6 o’clock position (Figure 1a). Of the more complex support structures, the clamped saddle support (Figure 1b) is particularly challenging for inspection, because of the large area covered by the saddle.
For inspection of the simple sleeper support locations, where the top half of the pipe is usually accessible, the semi-quantitative Pipe Support Tool was developed by Shell in the late 1990’s. It makes use of ultrasonic shear waves travelling around the pipe in the circumferential direction, where probes are set up in pitch catch position. The interaction of the ultrasonic waves with possible wall loss at the 6 o’clock position leads to changes in the received signal amplitude. The Pipe Support Tool is a fast & simple screening tool capable of distinguishing between no or light (<30%), moderate (30-50%) and serious (>50%) local wall loss. It can be applied on pipe diameters ranging from 3” to 18”, and of various thicknesses.

(a)  (b) 

Figure 1. Simple sleeper support (a) and a typical clamped saddle support location (b).

On pipes with clamps at support locations, the Pipe Support Tool is not applicable anymore because of top access restrictions. Removing the clamps would be required, which may be possible in some cases. However, if the pipe (also) rests on a saddle, then the Pipe Support Tool methodology will still detect wall loss, but won't be able to give any size indication of the wall loss anymore, because of the possible extended affected areas under the saddle (not only local at the 6 o'clock position). If on top of that the pipe size increases well above 18", another intermediate range ultrasonic approach is needed to inspect pipes at clamped saddle support locations non-intrusively. This paper will describe the application of the ultrasonic Multi-Skip inspection technique for this purpose.

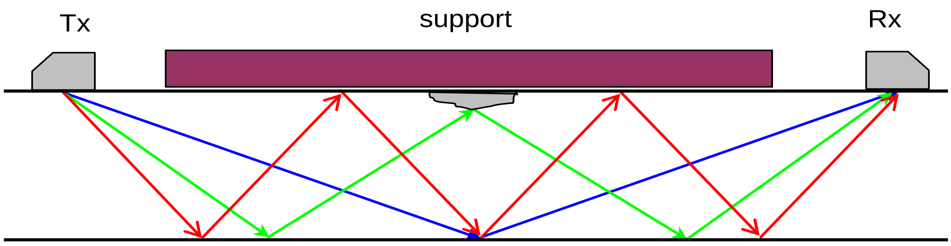

Figure 2. Basic ultrasonic Multi-Skip transmission set-up;
the 1-skip (blue), 2-skips (green) and 3-skips (red) ray paths are shown.

2. The Multi-Skip Inspection Method

2.1 Basic Principles

The principles behind Multi-Skip (or M-Skip®) have been very well described [1]. Here a short explanation will be given in order to show the complexity of a basically simple approach. The ultrasonic Multi-Skip method is based on the use of shear waves in a transmission set-up, where the source probe is located on one side of the support and the receiver probe on the other side, aligned in the axial direction of the pipe (figure 2). Many ray paths exist, which correspond to different skips signals. One skip is defined as a wave coming from the top surface, reflecting from the back and arriving at the top again.
The presentation in the form of rays (figure 2), may lead to confusion. The rays suggest merely discrete (local) interaction with the surfaces, while in reality a wrapped ultrasonic wave front is propagating through the material, interacting multiple times with all points on both surfaces. This is illustrated by the computational finite-difference modelling snapshot shown in figure 3. The amplitudes of the skip responses depend on the intensity of the wave field, which is determined by the beam spread (bundle characteristics) of the transducers.

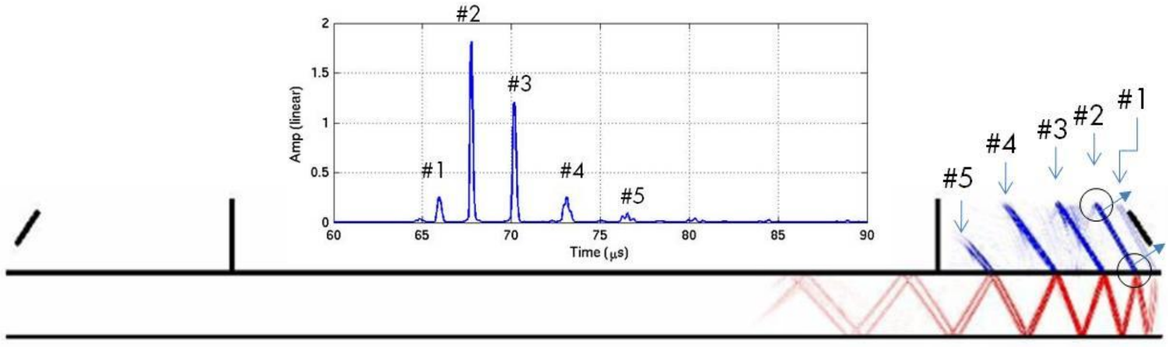

Figure 3. A snap shot of an ultrasonic wave field propagating through a plate, with the source at the left hand side; the receiver on the right hand side will record a series of (skip) signals.

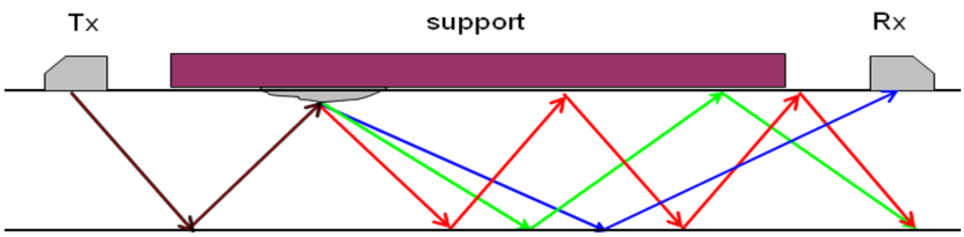

Figure 4. Coverage of Multi-Skip – any wall loss will act as a secondary source.

2.2 Multi-Skip Wave Propagation and Responses

Not all parts of the wave front that interacted with a particular point at the surface will reach the receiver location. At the receiver location, only (discrete) parts of the wave front will be recorded, while other parts are missing the receiver crystal in the defect-free situation. This can be seen in figure 3 (parts of the wave front indicated by the small circles). One might think that this could potentially lead to missing defect responses when the wave front interacts with local wall loss somewhere on its way between the probes. This, however, is not the case, because at the location of the wall loss diffraction/refraction will take place. In other words, the local wall loss area will act as a secondary source, sending waves into a range of directions. The diffracted/refracted wave front will in fact travel along alternative paths, as is shown in Figure 4. Hence, in practice, any localised area of wall loss will generate a response which will be recorded by the receiver, independent of the location of the wall loss with respect to the receiver.
It is worth mentioning that the Multi-Skip method is very sensitive to the presence of any wall loss. This is shown in the elastic modeling examples of figure 5. This means that it generally won’t be difficult to prove from the Multi-Skip response signals that no wall loss is present.

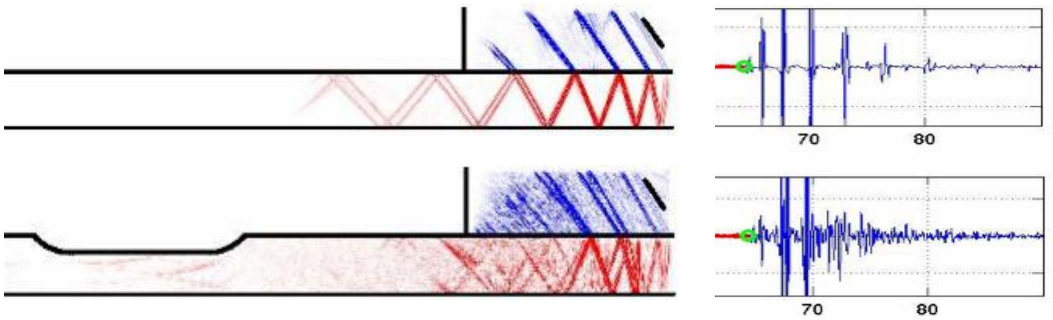

Figure 5. Snap shots comparing the wave field interaction with wall loss to the defect-free situation; notice the significant change in recorded response.

2.3 Calculating Wall Loss

In practice, Multi-Skip measurements are made with scanning ultrasonic Time of Flight Diffraction (ToFD) equipment, providing grey-level plots showing amplitude as function of scan position (x-axis) and time (y-axis), as shown in figure 6.
The general (average) wall thickness can be calculated from the arrival times of a series of skip signals using a least-squares fit algorithm. A local wall loss response will show up as an arc-type signal somewhere between two skip signals (see right picture in figure 6). Although there is a non-linear relation between the travel time of a skip signal and that of a local wall loss response, it is not difficult to calculate the local wall loss based on the difference between the skip and the wall loss signal arrival times. For the slug catcher configuration, the relation between wall loss and travel time difference (with respect to a skip signal) is almost linear.

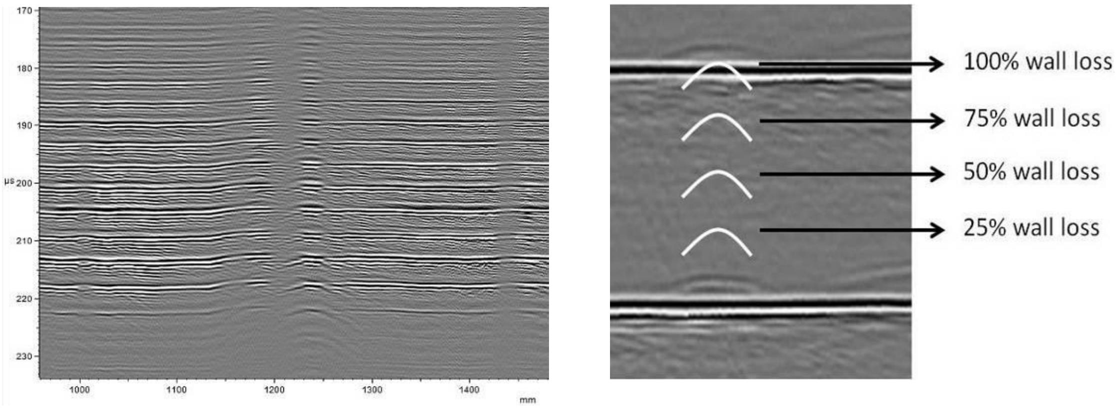

Figure 6. A ToFD representation of Multi-Skip measurements; interaction with local wall loss results in the earlier arrival of the defect signal.

(a) (b) (c) (d)

Figure 7. Schematic representation of four different characteristic Multi-Skip wall loss responses resulting from four different wall loss areas (time axis vertical and scan direction horizontal).

Generally, four different wall loss profiles can occur, which have distinctly different Multi-Skip responses as shown in figure 7:

1. Short in the axial as well as in the circumferential direction (figure 7a);
2. Short in the axial and long in the circumferential direction (figure 7b);
3. Long in the axial and short in the circumferential direction (figure 7c);
4. Long in the axial as well as in the circumferential direction (figure 7d).

From the Multi-Skip responses shown in figure 7 it is clear that if a wall loss defect is longer in the axial direction (along the line between the probes) than one skip distance, the skip signal is interrupted. This is an important indication, because the Multi-Skip method only provides arrival time difference and does not discriminate between an area of wall loss being hit once or more times by a particular skip signal. Hence, the wall loss values calculated from the Multi-Skip wall loss response arrival times are worst-case values. So, for example, if a skip signal interacts 3 times with an area of 2 mm wall loss, the corresponding Multi-Skip response will indicate a total of 6 mm (accumulative) wall loss.
Typical Multi-Skip responses as shown in figure 7 have been observed on test samples and in practice. Continued recording of the defect-free skip signal is a reliable indication of having a truly local defect of which the wall loss, as calculated from the arrival time differences between skip and defect signals, is accurate (and not an overestimation).

3. Multi-Skip Support Inspection Applications

3.1 Slug Catcher at Shell UK's St Fergus Gas Plant

3.1.1 Description of the structure
In 2010, the condition of the slug catcher of St Fergus Gas Plant (commissioned in 1982) had to be established in order to prove that it is still fit for service. The slug catcher is a huge steel structure, consisting of 13 parallel 275 m long pipes of 36" diameter and ~34 mm wall thickness, made of fine grain carbon manganese steel in accordance with API-5XL60 and

operating at ambient temperature. Most parts of the slug catcher are accessible for conventional inspection techniques and both internal as well as external degradation can be readily detected. Assessing the integrity of the slug catcher pipes at the clamped saddle support locations (as shown in figure 1b), however, has proven to be difficult. Since water ingress may have occurred in any space between the saddle and the pipe, external wall loss corrosion may have taken place over the years. Due to the construction of the clamped saddle support, identifying wall loss using conventional non-destructive testing methods is not possible. There were 143 clamped saddle support locations which had to be inspected. At the support location, the pipes were once painted with a primer and covered with a bitumen wrap.

3.1.2 Minimum detectable wall loss

Based on corrosion and fitness-for-service calculations, it was required to demonstrate that no wall loss defects deeper than 4 mm were present. This set the wall loss detection threshold for the inspection technique. However, the sensitivity of the inspection technique is also depending on the aspect ratio of the wall loss area (diameter/depth). From the expected corrosion morphology it was concluded that the inspection system for the slug catcher clamped saddle support locations should be sensitive enough to detect a (semi-spherically shaped) corrosion area with an aspect ratio (diameter over depth) as low as 10. With a minimum detectable wall loss of 4 mm, this translates into a wall loss area diameter of 40 mm. Hence, the inspection technique should be sensitive enough to detect defects of 4 mm deep (or deeper) with a diameter of 42 mm (or larger). In this case, with 36” diameter and an approximate 34 mm wall thickness, such an area of wall loss is much smaller than the detection limit (~9% cross-sectional wall loss) of the Guided-Wave technique.

3.1.3 Multi-Skip sensitivity requirements

In the case of the St Fergus clamped saddle support, 1.6 m had to be covered: 1.4 m support width + friction clamps and probes located 100 mm from the start/end of the support in order to be able to detect wall loss under the friction clamps and at the edges of the support. The range limitation of the Multi-Skip technique will mainly depend on the roughness of both inner and outer surface (scattering the signal), the presence and type of paint layer (absorbing/disturbing the signal) and the quality of the probes/equipment (signal quality).

The minimum detectable wall loss in case of the St Fergus slug catcher at the clamped saddle supports was set to 4 mm, with a diameter of 40 mm. An ultrasonic response from such a relatively small wall loss defect will be of considerably lower amplitude than that of a regular skip signal response. The sensitivity of the system is therefore determined by its dynamic range, i.e. by the achievable signal-to-noise ratio (SNR).

A 60 degree probe angle was found to be most suitable for Multi-Skip inspections in this case. A theoretical Multi-skip calculation model has been used with this angle to determine the amplitude difference between the strongest skip signal and the response from a spherical wall loss defect for a range of diameters. Obviously, the smaller diameter of the defect, the lower the noise level has to be in order to see the defect response in a Multi-Skip measurement. According to the calculations, in case a 40 mm diameter defect has to be detected, the minimum required SNR level has to be 12 dB. The depth of the defect is assumed not to have an influence on the local wall loss response or skip signal amplitude (for wall loss <<50%).

3.1.4 Multi-Skip scanning accuracy requirements

Apart from the amplitude sensitivity of the method with respect to detecting certain defects, there are requirements regarding the accuracy of the scanning measurements, which is largely dependent of variations in arrival time. With Multi-Skip, the presence of wall loss is determined by measuring (changes in) arrival times. Arrival times are depending on the

Figure 8. Multi-Skip scanner and probe assembly as developed & constructed by Sonomatic Ltd.

distance which the ultrasonic signal has travelled and that is not only a function of wall thickness, but also of probe distance. In order to be able to attribute a change in arrival time of a Multi-Skip response to a change in the wall thickness, the probe centre separation (PCS) should be kept constant. In order to keep the PCS constant it is not sufficient to make sure that the scanner rings are fitted at exactly the same distance for all positions around the pipe. It is also required that the probes shall remain in-line (facing each other) to within 2 degrees. This was achieved with probes travelling along a fixed track and scan motors which are electronically (master-slave) coupled (see left picture in figure 8).

3.1.5 Probe selection

Broadband frequency probes were selected, with a crystal size of 12 mm, a centre frequency of 2 MHz and an angle of 60° to meet the SNR (12 dB) requirement. Higher centre frequencies (like 5 MHz) may generate a shorter wavelet, but because of the long travel path and many surface interactions, most higher frequencies will be strongly attenuated above 2 MHz. With respect to the main angle of incidence, a 60° angle has found to be optimum in this configuration, since the time separation between skip signals is larger than with 70 degrees, while the signal is interacting fewer times with the surface (less signal loss) than 45 degrees. As can be seen from the right picture in figure 8, probes were equipped with Multi-Skip and 0-degree transducers in order to be able to simultaneously measure both signals. The 0-degree signals allow for the determination of the pipe wall thickness at both sides of the support, so possible general internal wall loss can be taken into account.

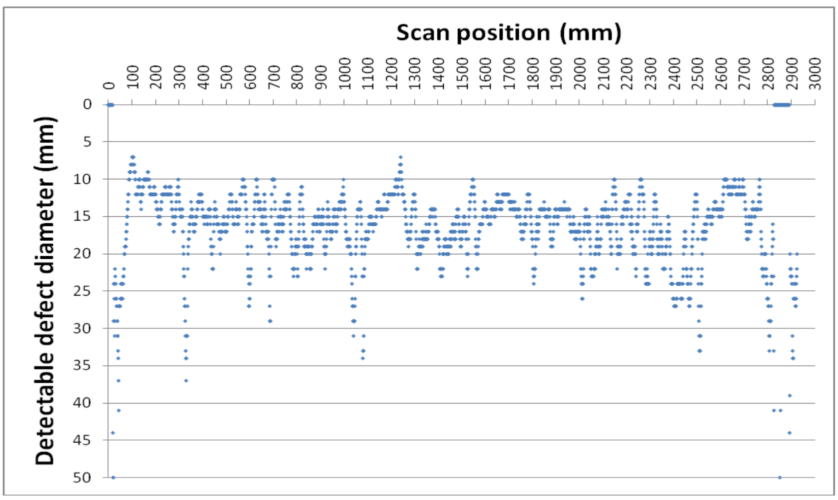

Figure 9. Example of a (field data) sensitivity graph in terms of minimum detectable wall loss area diameter instead of SNR, using a conversion from SNR to defect diameter as calculated by a theoretical model.

3.1.6 An alternative way to track sensitivity

In practice, it is fairly difficult to meet >12 dB SNR along the full scan, because of the amplitude reduction due to local surface roughness, the presence of coating layers and probe alignment variations. In order not to miss a 40 mm diameter wall loss defect, the sensitivity level shall not drop below 12 dB for over 40 mm scan length. However, if this requirement is locally not met during an inspection, this would mean that the entire inspection would fail. In order to avoid such problems in practice, it is suggested to look at sensitivity in a more dynamic way. Instead of tracking the SNR as sensitivity level, the diameter values of the corresponding wall loss defects are used as sensitivity level. For instance, instead of discarding the whole scan because of a local drop below the 12 dB threshold, a local sensitivity to 50 mm diameter defects could be regarded tolerable if no wall loss is detected anywhere in the vicinity of that location. A sensitivity graph of a Multi-Skip scan could therefore look like the one shown in figure 9.

Figure 10. Smart access options: movable scaffolding on rails (after removal of stairs) and inflatable weather protection.

3.1.7 Multi-Skip inspection results from the St Fergus slug catcher

After successful testing of the scanner and probe set-up on a real-size mock-up with artificial wall loss defects, the complete inspection of 143 supports was performed by Sonomatic Ltd in 40 days. Contributing to this achievement were the deployment of smart access solutions, in the form of movable scaffolding (on rails) and inflatable weather protection (see figure 10). All recorded data sets met the required data quality (sensitivity and accuracy) requirements to an acceptable level and no significant wall loss was observed. Minute variations in the general wall thickness (0.1-0.4mm) were detected. Such local variations in wall thickness in the circumferential direction seem to be constant in the axial direction and could be regarded as very shallow “grooves” resulting from the manufacturing process. The corresponding Multi-Skip responses of figure 11 show good agreement with the local zero-degree wall thickness variations as measured at the probe locations on either side of the support.

It has been found that the average wall thickness values calculated from Multi-Skip responses are generally a little higher (0.5 - 0.8 mm) than the 0-degree values (see figure 11). The exact reason for this discrepancy has not been determined yet, but is believed to be caused by a combination of possible phenomena: wave velocity variations, anisotropy of steel and/or coupling layer variations.

Because of the bitumen wrap around the full pipe at the support locations, no external wall loss corrosion was expected. The Multi-Skip inspection appeared to be an excellent technique to prove just that, as it is highly sensitive to the effect of relatively small areas of wall loss. It could be shown that the sensitivity of the Multi-Skip measurements was sufficiently high to prove that the absence of local wall loss indications (arc-type responses between the skip signals) actually meant that no local wall loss is present.

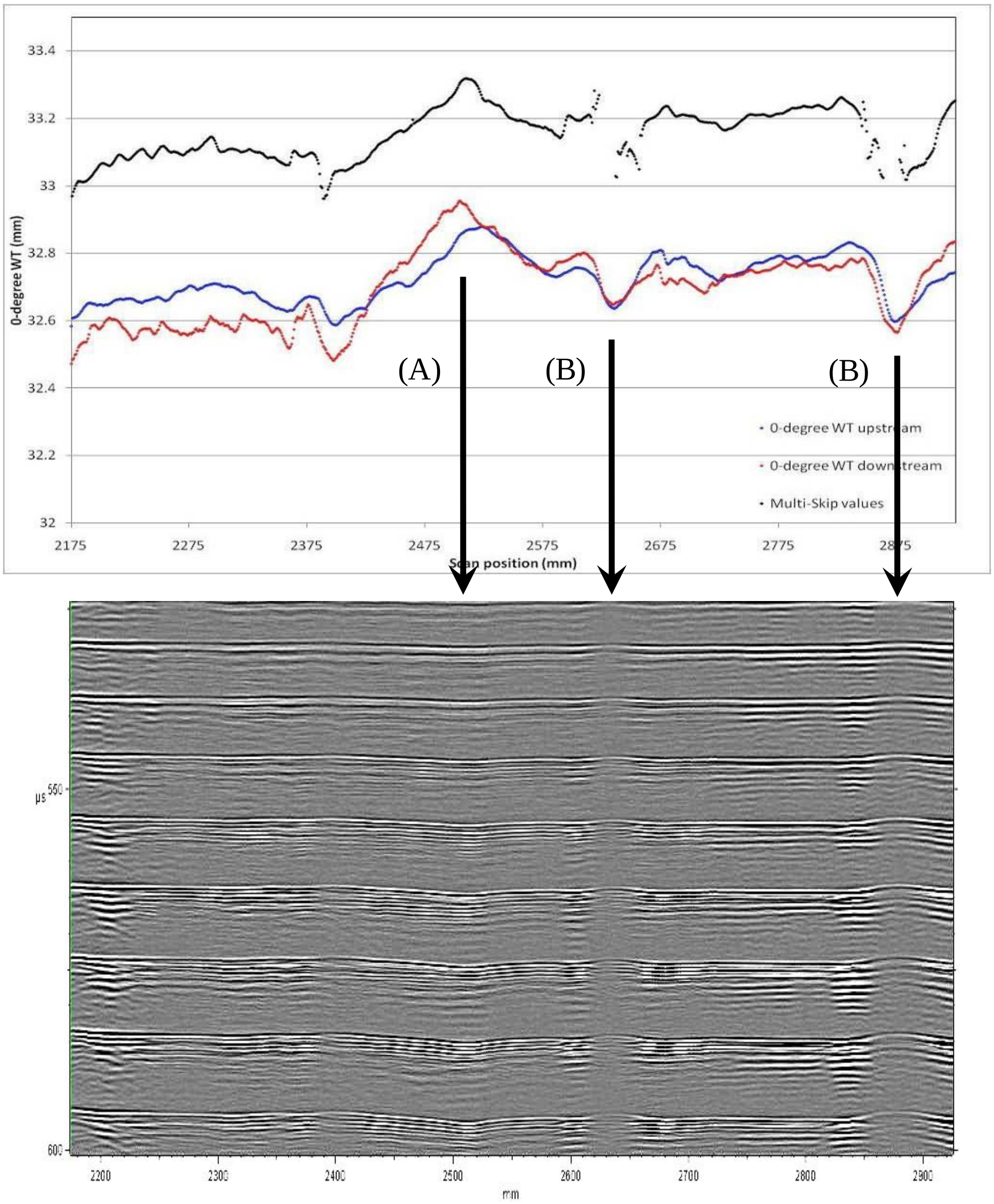

Figure 11. The Multi-Skip responses and the calculated average wall thickness as a result of minute local circumferential variations in wall thickness: dipping skips for a locally thicker ("strip") part of the pipe at position (A) and gradually bulging skips for locally thinner ("groove") parts of the pipe at positions (B); the red & blue lines are the 0-degree wall thickness values from both sides of the support; graphs calculated with NTPLOT software from ESR Technology Ltd..

3.2 Flare Line at Shell UK's Mossmorran Gas Plant

3.2.1 Description of the approach

From the experience gained with the inspection of the clamped saddle support locations of the slug catcher at St Fergus Gas Plant, it was decided in 2011 to apply a similar approach to the clamped saddle support locations of the Mossmorran 20"-48" flare line. The big difference between the two structures is the wall thickness: the slug catcher is ~34 mm thick, while the flare line has a nominal wall thickness of ~10 mm. This will cause the Multi-Skip signals to come in shorter after each other. Since, overall, the Multi-Skip signal (wavelet) itself will have the same length, this means that there is a chance that the skip signal will obscure any local wall loss response coming in between two regular skip signals. Applying a broadband (short) Multi-Skip wavelet is therefore crucially important.

Despite the shorter probe-centre separation (PCS) in the case of the flare line (~600 mm versus ~1600 mm for the slug catcher), the smaller wall thickness caused the ultrasound to skip more times between the source and receiver transducers. Especially in case that the reflecting surfaces are rough because of general wall loss, this will result in a lower amplitude of the detected skip signals, which may even get lost in the noise. In order to assess general wall loss despite of surface roughness, it was decided to combine Multi-Skip inspections with CHIME inspections. CHIME signals [2] are better suitable to travel along rough surfaces and in the case of an extended area of wall loss, they will still be able to indicate a degree of degradation, while the Multi-Skip signals are lost. If a local area of wall loss is present, the CHIME signals won't always be able to detect that, yet the Multi-Skip signals will be very sensitive to that. Hence, CHIME was applied to identify (the degree of) general wall loss, while Multi-Skip is applied to detect (and size) local wall loss.

Pipe diameters included in the scope covered 24”, 30”, 36”and 48”. All wall loss of 3.5mm or more was considered intolerable according to the flare line specification. Wall loss of 3mm or more was designated to be classified as “significant”. The ultrasonic screening inspection by applying a combination of CHIME and Multi-Skip techniques was performed by Sonomatic Ltd with the use of the same automated scanning set-up as used for the St Fergus slug catcher (figure 8). The total number of clamped saddle supports inspected was 259. The same type of sensitivity and scanning accuracy requirements were applied as in the slug catcher case.

3.2.2 Multi-Skip inspection results from the Mossmorran flare line

The semi-quantitative CHIME inspection results were classified in three degrees of wall loss: <10%, 10-30% or >30%. This classification in terms of general wall loss was governing in ranking the supports on priority for follow-up inspection (radiography, lifting). The Multi-Skip inspection results were analysed for the presence of local (diameter <50 mm) wall loss indications. In extended corroded areas, the surface roughness prevented Multi-Skip signals to be detected and “black-outs” could be seen in the Multi-Skip scans. Not surprisingly, these “black-outs” corresponded well with the highest wall loss areas identified from CHIME data. Despite the lower wall thickness, good quality Multi-Skip signals could be generally collected. An exception to this were locations where a fresh (thicker) paint layer was present. The paint layer caused extensive “ringing”, which resulted in a significantly longer wavelet of the skip signals. This made it virtually impossible to detect (let alone size) local wall loss indications. Furthermore, in areas where extended areas were affected by corrosion, surface roughness caused the Multi-Skip signals to scatter and die out before reaching the receiver. The clamps of a support were removed to check the condition of the top half of the pipe. In figure 12 the surface condition of the pipe at the clamp locations is shown. The wall loss under both clamps lined up and was each in the order of 1 mm (scan range around 450 mm). In the CHIME scan (figure 12) the signal amplitude is reduced at the area around 450 mm, indicating wall loss. The wall loss as rated by CHIME (>30%, meaning more than 3 mm wall

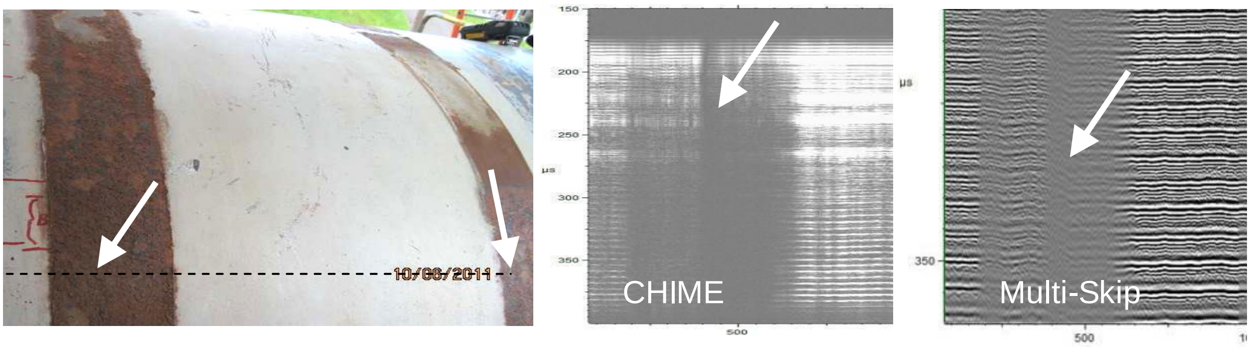

Figure 12. Picture of the pipe in the scan range around 450 mm after clamp removal and CHIME data with the area classified as >30% wall loss and corresponding Multi-Skip data (arrows indicate ~1 mm wall loss areas).

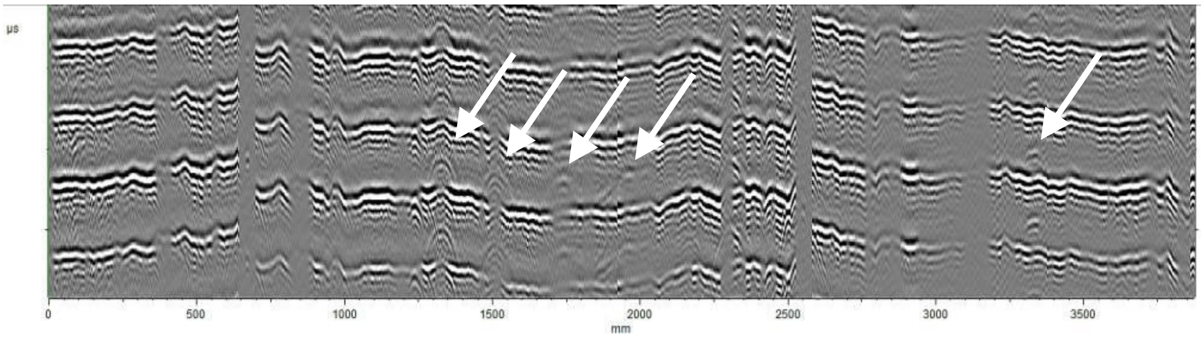

Figure 13. Full circumferential Multi-Skip scan data with local wall loss responses indicated by the arrows; longitudinal welds are located at ~700 mm and ~2550 mm.

loss) is slightly overestimated. Analysis of the Multi-Skip responses at the same scan range resulted in a measured maximum of 2 - 2.5 mm wall loss. This is in fair agreement with the actual condition, because the Multi-Skip technique measures accumulative wall loss (1 mm at both sides).
In some cases, good quality Multi-Skip data revealed local wall loss indications, which were not detectable by CHIME . An example is shown in figure 13. These local wall loss responses correspond to approximately 40-50% wall loss. Where the skip signal is not interrupted, this indicates that the arc-type of responses originate from very local wall loss areas, which have only been hit once by the regular Multi-Skip signal (so, no over-sizing expected).

4. Conclusions

The ultrasonic Multi-Skip inspection technique has made a modest entry in the world of advanced ultrasonic inspection methods. As an intermediate-range inspection technique, it has been shown that the technique is particularly useful for the inspection of pipes at clamped saddle support locations. Multi-Skip inspections were done on 20”- 48” diameter pipe of 34 mm or 9.5 mm wall thickness. Although sensitivity and accuracy requirements are challenging, it has been shown that scanning equipment can be applied to meet those requirements in the field. It has been shown that very small general wall thickness variations (0.1-0.4 mm), originating from the pipe fabrication process, can be detected by Multi-Skip. In addition to that, accurate local wall loss values can be obtained from Multi-Skip responses. In the presence of thicker (fresh) paint layers and over extended (corroded) areas with rough surfaces the Multi-Skip technique is not so successful. The paint layer causes excessive “ringing” of the Multi-Skip signal and makes the detection of local wall loss indications impossible. Extended rough surface areas cause scattering of the Multi-Skip signal, indicating the presence of corrosion, yet resulting in a loss of the Multi-Skip signal at the receiver end. Despite certain limitations, the Multi-Skip inspection technique, with its high sensitivity to local wall loss, appears to be a welcome addition to the currently available Guided-Wave and CHIME inspection methods for inaccessible locations, like clamped saddle supports.

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