REPORT

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Report title

Applicability of Acoustic Pulse Reflectometry to injector and heat exchanger tubes with typical manufacturing flaws

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Accreditation and certification note

Investigations covered in this report on the topics mechanical technological tests of metallic materials, technological tests of metallic parts or components, metallographic examinations of steel materials, corrosion tests on different steel materials and tests on effectiveness of organic coatings were carried out in the SZMF laboratories, which are accredited by "Deutsche Akkreditierungsstelle GmbH" (German Accreditation Body, DAkkS) according to DIN EN ISO/IEC 17025. The accreditation applies to the test methods listed in the certificate.

Investigations presented in this report with respect to Eddy Current Testing, Flux Leakage Testing, Magnetic Particle Testing, Penetrant Testing, Radiographic Testing, Ultrasonic Testing were carried out by or supervised by Testing Personnel certified according to EN 473 level 3 and/or having an employer certificate according to SNT-TC-1A level III.

Results / Summary

The Acoustic Pulse Reflectometry (APR) is a testing method for tubes as they would typically be used in heat exchangers and boilers. In this report we dealt with two questions: Is it possible to apply the APR technology also to tubes with very small inner diameter (down to 4 mm)? Can APR detect typical manufacturing defects (of course depending on the manufacturing process)?

The answer to the first question was not obviously “yes”, because it is not easy to insert an acoustic pulse with sufficient energy into a tube with such a small inner diameter. But the experiment showed that it is possible, although the maximum testable tube length is decreased in comparison to tubes with larger inner diameter.

To answer the second question, samples with and without typical manufacturing defects from Salzgitter Mannesmann Stainless Tubes (MST) and Salzgitter Mannesmann Precision Tubes (SMP) have been collected. In cooperation between SZMF and AcousticEye these samples have been measured with the APR system Dolphin G3™.

In the case of MST tubes typical defects are very small cracks inside the tubes. The volume of these defects is very small and thus very hard to detect for the APR system. Nevertheless, some chips, dirt and the felt plugs could be detected clearly by the Dolphin G3™. Finally, artificial holes have been detected excellently even if they were located at the end of the tube.

The tubes of the second supplier (SMP) have the typical dimensions for APR inspection. Characteristic manufacturing defects here are burned-in oil and dirt, grooves, chips and marks from mandrel breaks. Regarding the sample tubes that contain these defects, we were not able to find those elongated flaws that do not cause an abrupt change in the inner cross-section but only a slow continuous one, like the burned-in oil and dirt and the grooves. If dirt changes the roughness of the inner surface significantly, it becomes noticeable by a higher noise-level. In future developments it could be possible to classify these signals also as defect indications.

In contrast, the flaws like chips and mandrel break marks were very reliably detectable. They cause an abrupt change in the cross-section and give a clear indication in the measured signal. The trials with the artificial chips show, that the Dolphin G3™ from AcousticEye can still reliably find chips with an area of 1 % of the inner cross-sectional area of the tube.

Comparisons of tube lengths determined by APR with manually measured lengths already provide promising results although the precise temperature was not known. The potential of APR for length measurement should be explored in further investigations.

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Contents

1 Introduction

The Acoustic Pulse Reflectometry (APR) is a testing method for tubes as they would typically be used in heat exchangers and boilers. It is able to detect defects that change the inner cross-section of the specimen, e.g. blockages, wall loss, holes, etc., and has some advantages over conventional inspection systems for these kinds of flaws. Its purpose is not to detect defects within the tube wall as inner cracks or flat slivers, as they do not change the inner cross section. The measurement time of the current APR system, Dolphin G3™ from AcousticEye, a pioneer company in the APR technology, is very short (about 10 seconds per tube), the tube only needs to be accessible from one side, tube bending doesn't have significant influence, and no probe needs to be inserted into the tube. Up to now, APR is mainly used to inspect tubes in already installed industrial systems like heat exchangers.

Salzgitter AG [1] is a steel and technology company with subsidiaries that also manufacture and sell steel tubes of different dimensions, starting from 4 mm up to about 1.5 m inner diameter. The question arose whether the APR technology can already be beneficial in the production process as additional or an alternative inspection system.

In a previous study of the Southwest Research Institute [2], the ability of detecting artificial flaws (blockages, thru-holes, etc.) has been analyzed for tubes of 19.1 mm and 25.4 mm inner diameter. In addition to this study, there are two main questions we would like to deal with here:

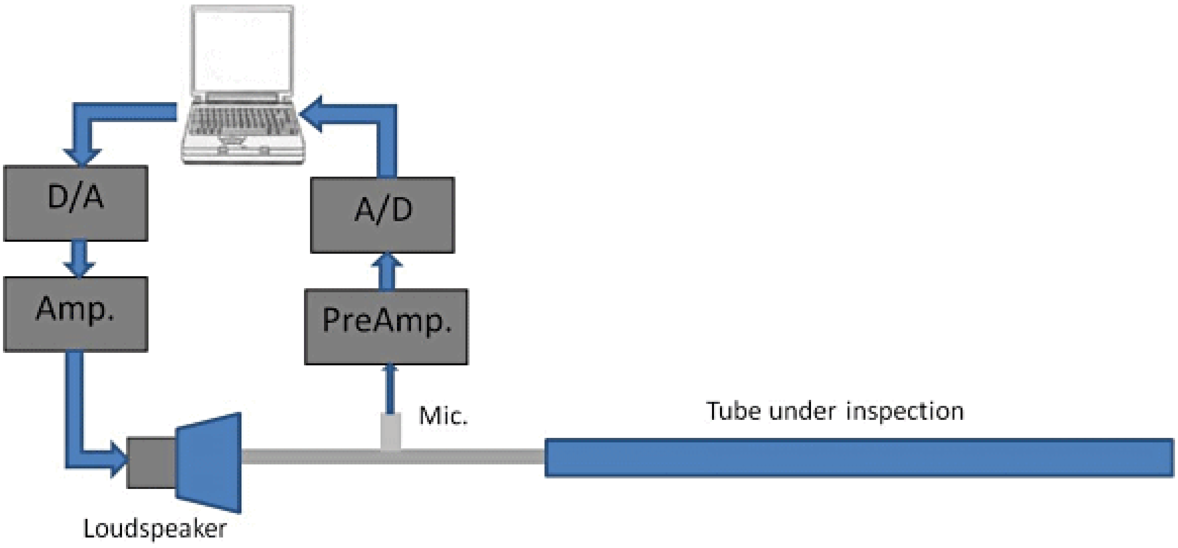
1) Is the APR technology also applicable to tubes with very small inner diameter down to 4 mm? Such dimensions are typical for injector tubes and the answer to this question is not obviously “yes”, because it is not easy to insert an acoustic pulse with sufficient energy into a tube with such a small inner diameter.

2) Is it possible to detect typical manufacturing defects? The kind of such defects depends on the manufacturing process. Typical defects would, for example, be corrosions, grooves, chips, marks of mandrel breaks, etc.

Regarding these questions, the Salzgitter Mannesmann Forschung GmbH (SZMF), the research company of the Salzgitter AG, performed cooperation with the APR developer and manufacturer, AcousticEye Ltd. SZMF gathered samples of tubes with and without typical manufacturing flaws, and produced representative artificial flaws. For this trial, two members of AcousticEye (one scientist and the sales director) visited the SZMF in Duisburg, Germany, with their equipment and performed measurements together with two researchers from the SZMF to analyze the questions mentioned above. The used samples, flaws, the procedure, and finally the results of this trial are described in this report.

2 Description of the APR Method

Generally speaking, the Acoustic Pulse Reflectometry (APR) is a technique to measure the acoustic response of a given system. With a loudspeaker as a source of sound, an excitation pulse is applied to this system and all the reflections are measured with a microphone. In our application the systems to be measured are tubes, and reflections are caused by changes in the cross-section. The key is that different changes in cross-section lead to different types and sizes of reflections. For example, reflections from blockages can clearly be distinguished from those from holes or wall losses.



In the sketch above, the design of an APR system is depicted. A computer generates a digital pulse or a well-defined sequence of pulses which are digital to analogue converted, amplified, and sent to a loudspeaker. The loudspeaker then generates a corresponding acoustic wave which travels through an interface tube (adapter) to the tube under inspection. Any defects or blockages in the tube that change its cross-section cause reflections that travel back up the tube and pass the microphone which is located in the wall of the interface tube. One reflection is always caused by the end of the tube.

In our trials we used the Dolphin G3™, the latest APR system of AcousticEye. This system has a very short interface tube. In order to be able to separate reflections from the tube under inspection itself and signals that have been reflected at the loudspeaker again, a first calibration procedure is necessary to measure the impulse response of the whole probe. This calibration is performed with an accurately defined calibration tube.

A second calibration serves to adjust the amplitude of the impinging pulse which depends on the intensity of the surrounding noises. For this, five measurements are taken on a typical tube under inspection with different pulse intensities. Afterwards, the optimal intensity is chosen.

3 Experimental setup

Measurements of the acoustic response described before were carried out in two tube sample sets of different manufactures.

Salzgitter Mannesmann Stainless Tubes (MST) [3] offers their customers austenitic corrosion resistant stainless steel tubes. Those seamless tubes and pipes are mainly used in the following industries: Chemical and petrochemical industry, power generation and environmental technologies, oil and gas applications and automotive industry. The investigated 30 samples of MST are stainless tubes for automotive industry and have a small inner diameter of 4 and 5 mm.

Salzgitter Mannesmann Seamless Tubes (SMP) [4] produces precision steel pipes for the energy industry, the chemical industry, in automotive, plant and machine construction, as well as for trade. The pipes are in steering systems, airbags or in the chassis, in boilers, power plants or refineries. The steel pipes are remarkable for their very thin wall thicknesses, and have defined surface quality and mechanical characteristics. Salzgitter Mannesmann Seamless Tubes pipes can be bent and widened and reprocessed for various uses. For the trials 33 tubes with inner diameters of 14.5 to 26 mm have been chosen. The exact dimensions of the used tubes which are divided into groups depending on dimensions are listed in table 1. All of them had a length of about 6 to 7 m.

	Dimension	**Inner diameter**	**Nr. of piece**	**Tube good / rejected**	**Type of flaws**
	MST				
Group 1	6 x 1 mm	4 mm	5	good	
	6 x 1 mm	4 mm	5	rejected	
Group 2	8 x 1.5 mm	5 mm	5	good	
	8 x 1.5 mm	5 mm	5	rejected	
Group 3	10 x 2.5 mm	5 mm	5	good	
	10 x 2.5 mm	5 mm	5	rejected	

	SMP				
Group 1	19.05 x 2.26 mm	14.53 mm	4	good	
	19.05 x 2.26 mm	14.53 mm	5	rejected	Burned-in oil, chips, marks of mandrel breaks
Group 2	21.00 x 1.50 mm	18 mm	1	good	
	21.00 x 1.50 mm	18 mm	9	rejected	Burned-in oil, chips, marks of mandrel breaks, grooves
Group 3	30.00 x 2.00 mm	26 mm	3	good	
	30.00 x 2.00 mm	26 mm	5	rejected	Burned-in oil, chips, burned-in dirt, marks of mandrel breaks
Group 4	25.40 x 2.96 mm	19.48 mm	2	good	
	25.40 x 2.96 mm	19.48 mm	4	rejected	marks of mandrel breaks, burned-in dirt, burned-in oil

Table 1: List of the used test tubes.

Flaws that may occur by production of MST tubes are typically small cracks and corrosions inside the tube. The delivered tubes which are labelled as rejected led to an indication during ultrasonic testing (UT) in the mill using a calibration sample with a notch of 0.1 mm (for 6 x 1 mm and 8 x 1.5 mm tubes) and 0.2 mm (for 10 x 2.5 mm tubes) depth, respectively. The regions of UT indications have been visibly marked outside the tube. The kinds of irregularities within the tubes which led to those indications were not known. For checking the behaviour of the AcousticEye system concerning corrosions, we artificially generated corrosions inside some tubes (no delivered test tube contained corrosions). Therefore a region within the tube has been roughened by a grinding stone, fixed at the end of a 1 m long rod (see Figure 1). This rod was fixed in a drill machine and inserted into the tube. After that a few millilitres of hydrogen fluoride were inserted at the roughened area and remained there for about one week. Hereafter, the tube was flushed with water. Unfortunately, the corrosions were very weak and did not produce any detectable blockage or change of surface for the APR system.

Further artificial defects in form of blockages have been used and will be described in one of the next chapters.

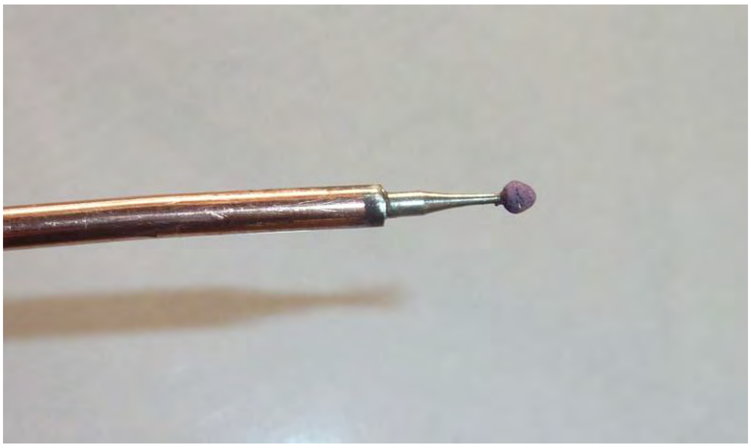


Figure 1: Rod with grinding stone used for roughening the inner surface of tubes.

SMP has to deal with flaws like burned-in oil within the tubes, chips, grooves, die marks and expansion or constriction by mandrel break. The exact positions of the defects were unknown within the test tubes. Some of the defects could be detected with an endoscope camera providing that those irregularities were near the end of the tubes. For qualitative conclusions artificial flaws for the SMP tubes have been prepared, too. They are described in the corresponding chapter.

During a measurement with the Dolphin G3™ at one end the other tube end was open. The measurements have often been performed from both sides of the tube. The duration for one measurement was set to 10 seconds.

Conventionally, the AcousticEye system is used for tubes with an inner diameter of 8 to 102 mm. For those dimensions different types of adapters exist to couple the acoustic impulse into the tube. This led to the need of an additional adapter for the tubes with an inner diameter of less than 8 mm. This adapter has been turned in our workshop and is shown in Figure 2.

Figure 2: Turned adapter for tubes with inner diameter smaller than 8 mm.

4 Procedure and results for MST tubes

4.1 Available samples

The tubes of MST can be divided into three different groups of ten tubes each, according to their dimension (cf. Table 1). In each group there were five tubes that caused indications at the Ultrasonic Testing (UT) after the production process. The other five tubes were labelled as “good”.
From each of the three groups we selected one good labelled tube to induce corrosions inside as described in the previous section. Including these tubes with corrosions, we had after all six tubes with defects and four without defects in each group.

The procedure than was as follows: We measured all 30 tubes without any further modifications from both tube ends (see following section) and analyzed the indicated defects. Afterwards, we inserted artificial flaws in some tubes at different positions and measured the tubes again (see section 4.3).

4.2 Measurements on unmodified samples

4.2.1 Results group 1 (6 x 1 mm)

In this group two tubes raised noticeable indications. The first tube was a good labelled one with an indication of an 80 % blockage at about 1.7 m. The signal of the measurement can be seen in Figure 3. After the tube has been cut it turned out that a felt plug was the reason for this blockage. MST closes the tubes with these kinds of plugs before shipping them to the customers.

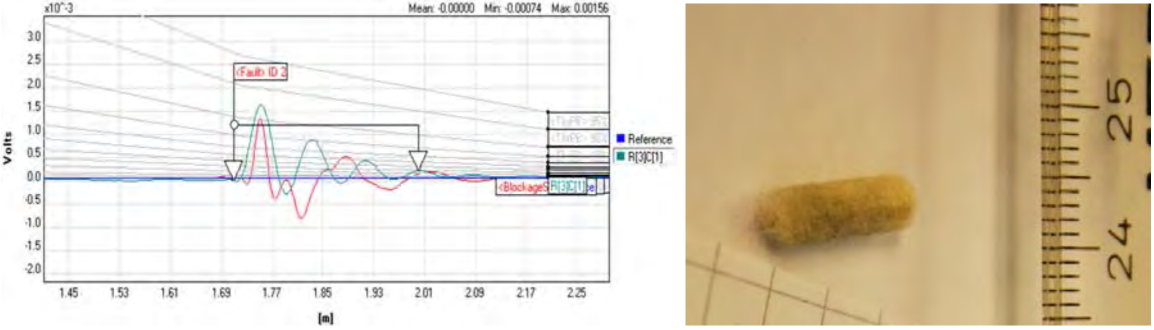


Figure 3: Left: Signal of the 80% blockage, right: felt plug which was found inside the tube.

The second tube showed already an indication during UT testing. The evaluation of the Dolphin G3™ system identified an erosion of 50 %. But after cutting the tube we found a blockage and a chip in this region (see Figure 4 for the measurement and a photo of the inside of this tube section).

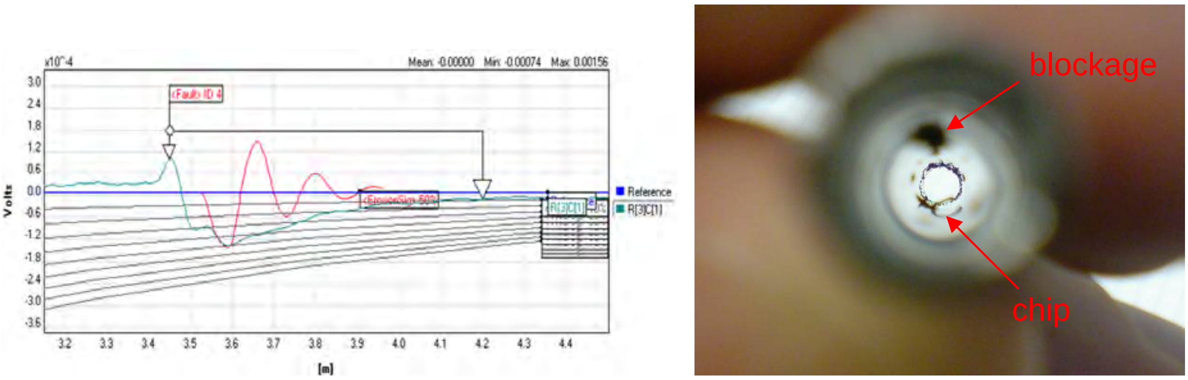


Figure 4: Left: Signal of the 50 % erosion, right: chip and blockage could be seen.

4.2.2 Results group 2 (8 x 1.5 mm)

In this group two indications occurred. The first irregularity was a sub-threshold blockage in a good labelled tube which can be seen in Figure 5. After cutting this tube, some loose, small chips could be found in there. This is an example for a flaw which cannot be detected by UT measurements, but by the APR system.

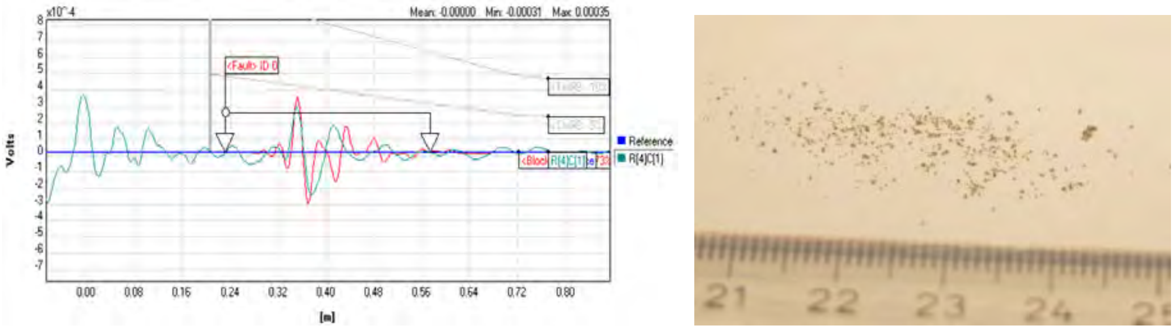


Figure 5: Result of a measurement showing a sub-threshold blockage in a good labelled tube.

The second flaw detected by APR was a small blockage at the end of the tube at about 5.85 m. After cutting the tube at the particular position a chip and some dirt particles appeared. The results are depicted in Figure 6.

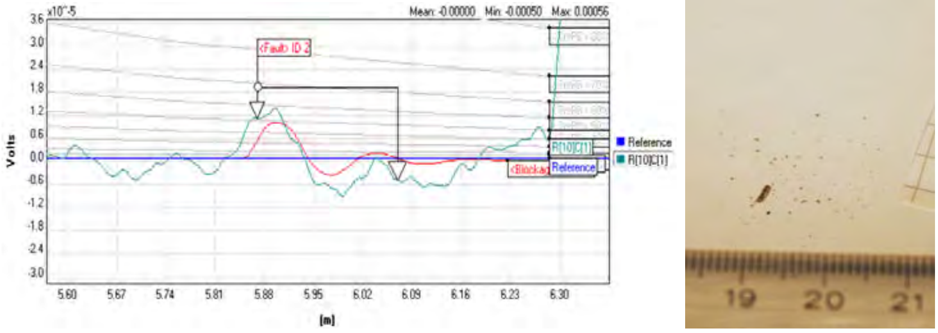


Figure 6: Indication of a blockage which turned out to be a chip at the end of the tube.

4.2.3 Results group 3 (10 x 2.5 mm)

In group 3 (inner diameter of 5 mm) an extended blockage was indicated by the APR system. By analyzing the inside of the tube it became clear that this indication is due to small particles inside the tube which were spread over a wider area of about 1 m. The result is shown in Figure 7.

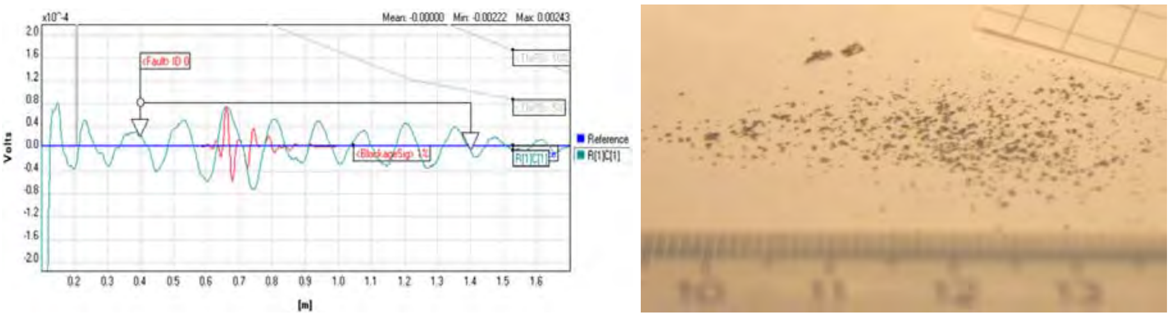


Figure 7: Indication of some particles spread over an elongated area inside the tube.

4.3 Measurements with artificial flaws

4.3.1 Blockages

To simulate simple blockages inside a tube, a piece of copper wire with a diameter of 1.2 mm and a length of about 31 mm has been inserted into a tube with inner diameter of 5 mm at positions 1 m, 2 m, 3.2 m, and 4.3 m. Results of the these measurements are depicted in Figure 8.

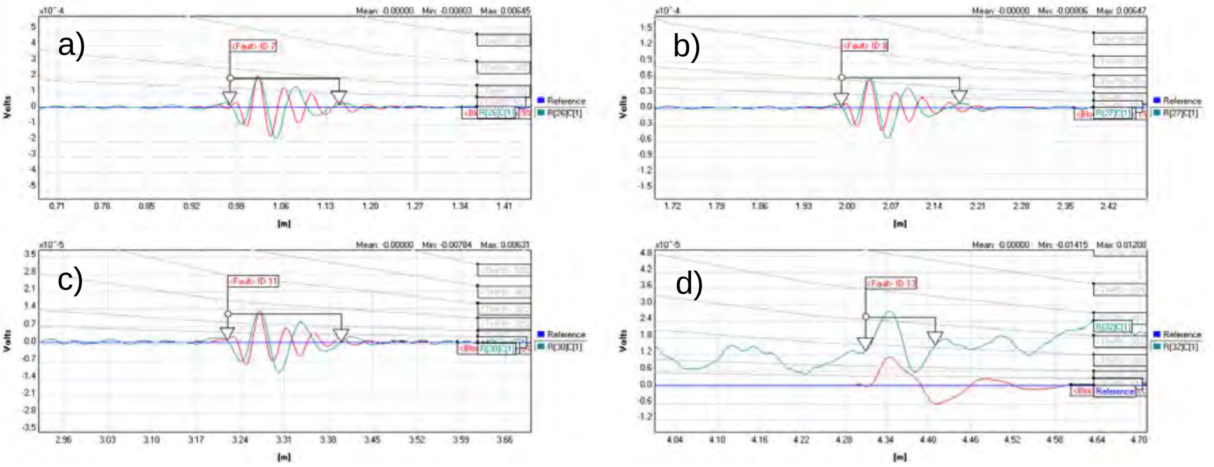


Figure 8: Indication of a copper wire (1.2 mm) inside a tube with an inner diameter of 5 mm. Position of the artificial flaw from the tube end: a) 1 m, b) 2 m, c) 3.2 m, d) 4.3 m

One can observe that the thin wire with a filling factor of about 6 % is clearly detectable at the distances 3.2 m or closer to the tube end from which the measurements have been performed. The blockage has also been detected at the 4.3 m position, but with a lower signal to noise ratio. Obviously, the energy of the acoustic pulse is smaller than in case of larger inner tube diameters. Hence, the maximum measureable length of these tubes is smaller. One reason for this is that it is more difficult to induce the same amount of acoustic energy into the small opening of small inner diameters. However, one has to keep in mind that the adapter we used for the trials was improvised. With a more optimised adapter, it would be possible to induce energy more efficient into the tube.

4.3.2 Holes

Even if holes are not typical defects for the manufactures, a few tests with drilled holes of 0.8 mm diameter have been performed. The positions of the holes were at several distances up to 5.5 m to the tube end. Each of those holes could be detected very clearly. Figure 9 shows the result of the farthest (5.5 m) hole.

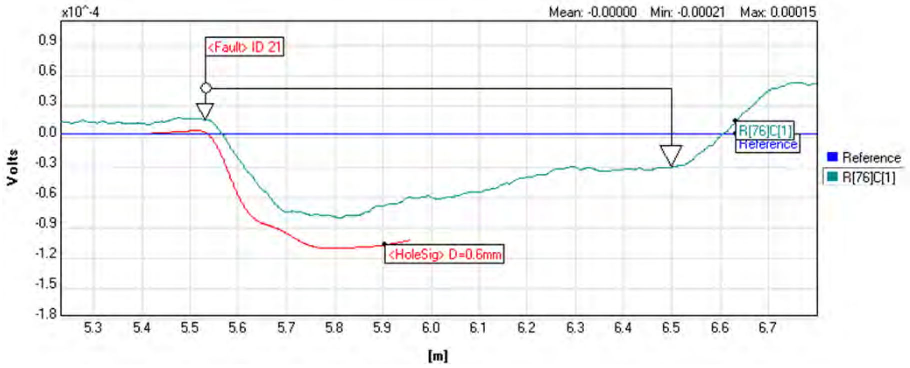


Figure 9: APR signal of a tube with a drilled hole at 5.5 m.

5 Procedure for larger tubes (SMP)

The second supplier that was interested in the APR technology was Salzgitter Mannesmann Precision GmbH, a European manufacturer of cold-drawn seamless and welded precision steel tubes.

5.1 Available samples

From the second supplier (SMP) we received 33 samples. Some of these tubes were labelled to contain certain flaws without specification of the flaws positions. The remaining tubes were specified as ”without artificial flaws”. According to the tube dimensions, they can be divided into four groups:

- Group 1: 9 samples of dimension 19.05 x 2.26 mm out of which 4 samples were without flaws
- Group 2: 10 samples of dimension 21 x 1.5 mm out of which only one was without flaws
- Group 3: 8 samples of dimension 30 x 2 mm out of which 3 were without flaws
- Group 4: 6 samples of dimension 25.4 x 2.96 mm out of which 2 were without flaws

Flaws that may occur by production of SMP tubes are typically burned-in oil and dirt, chips, grooves, and marks where the mandrel, a part of the inner die in the production process, broke. The latter one consists of an abrupt change in the inner diameter (an example is shown in Figure 10). The chips can occur loose or they can be fixed and reach into the interior of the tube. Examples of such chips are shown in the subsequent sections (e.g. Figure 13).

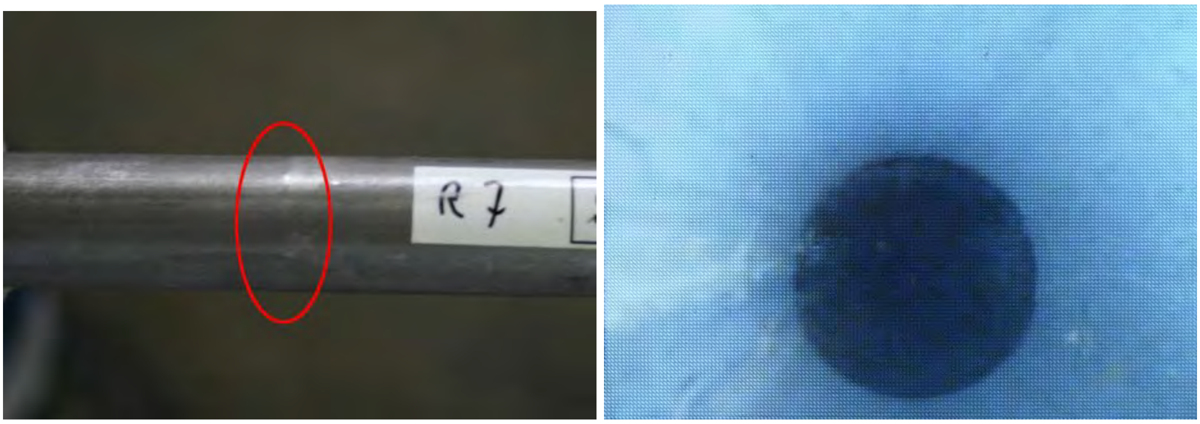


Figure 10: Marks of a mandrel break: The inner diameter changes abruptly. Left: View from outside, right: The inside at this change, seen by an endoscope.

In contrast to these flaws, the burned-in oil and dirt and the grooves (some kind of scratches) have a quite large extent in axial direction which can be up to several meters. They don't exhibit a rapid change in the tube inner cross section but only a continuous one.

5.2 Performing measurements without artificial flaws

After the necessary calibration, all tubes have been measured from both sides. The results have been analyzed with respect to the flaws which are specified therein. It was not possible to find all kinds of specified flaws, but some could be found very reliably.

Furthermore, we got some indications in tubes that have been classified as defect free. If these indications were close enough to one end of the tube we analyzed them with an endoscope. In addition, we cut out tube sections in which the indications were located and analyzed them further. By this, we found several flaws and dirt which was not specified by the manufacturer.

In the following, the results are ordered by the groups defined above.

5.2.1 Results group 1 (19.05 x 2.26 mm)

In this group there were two tubes with burned-in oil and small dirt. The indications of the burned-in oil were spread out over the corresponding region and were not local as from other defects. The indications were manifested as a generally "noisy" signal, as opposed to the signal obtained from measuring clean tubes. (see Figure 11).

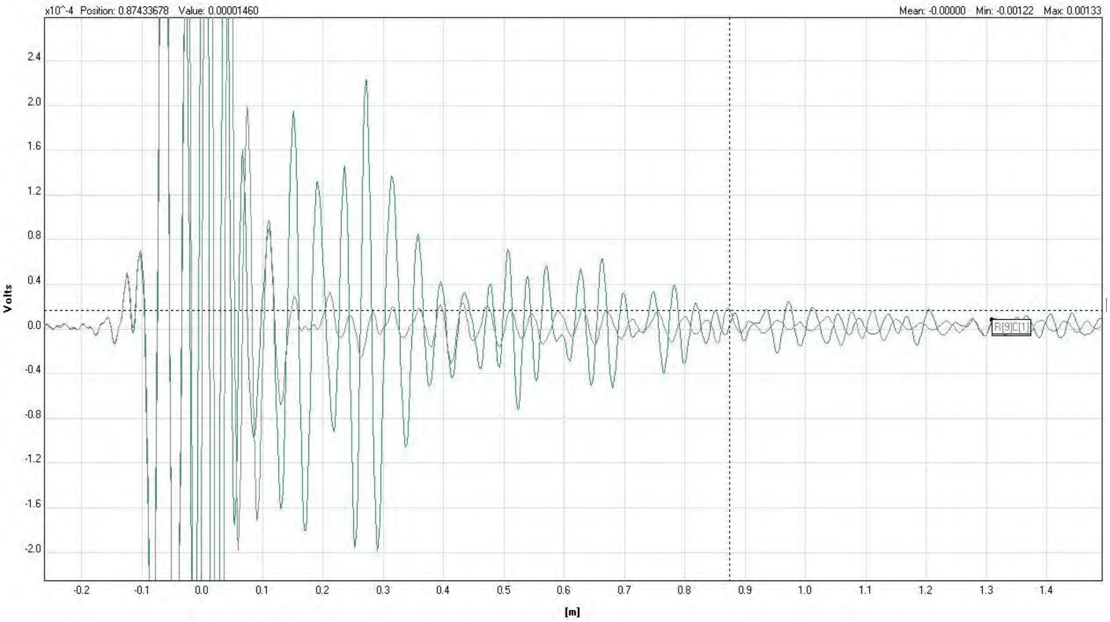


Figure 11: Difference in the noise level between a tube with burned-in oil and dirt (green curve) and a "clean" curve (gray curve).

Furthermore, there were three tubes with marks of mandrel breaks. All three marks could be found very clearly (see Figure 12, left hand side for an example) from both ends of the tubes.

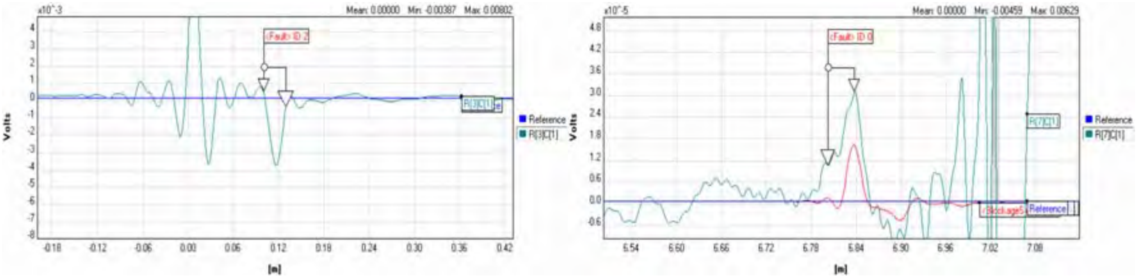


Figure 12: Left: Signal of the mandrel break marks, right: signal of the chip.

Finally, we found one chip in a tube which was classified as defect free by the manufacturer. The corresponding APR-signal is shown in Figure 12, right hand side. We cut out a section of the tube that contained the chip and took a picture of it in the inside. Afterwards, we removed the chip from the tube and took a picture of it outside (see Figure 13).

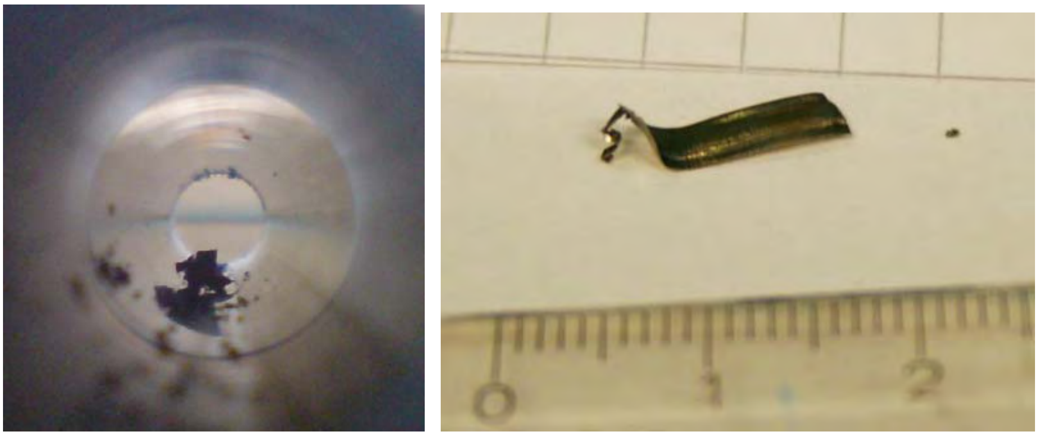


Figure 13: A chip that we found in a tube which was not specified to contain flaws.

5.2.2 Results group 2 (21 x 1.5 mm)

In this group nine tubes contained grooves, five of them also burned-in oil and dirt, and three tubes contained a mark of a mandrel break. Again, the burned-in oil and dirt and also the grooves gave indications that appeared as a higher noise level in the measurements. This seems to depend on the amount of burned-in dirt. If the inner tube surface is significantly rougher due to the dirt, the noise level in the measurements is increased.

Regarding the three marks of the mandrel breaks, in the first pass from one side we only found two of them. The reason was that the missing mark was only about 1.5 cm apart from the end of the tube. By this, its signal was hidden in the impinging pulse signal. But in the second pass, in which we did the measurements from the other end of the tube, all three marks could clearly be seen.
Again, we found some flaws which were not specified before: A plastic chip and dirt made from some kind of paper (see Figure 14). Their APR signals are shown in Figure 15. The dirt was distributed over about 0.5 m, while the chip gives an indication at one clear local position.

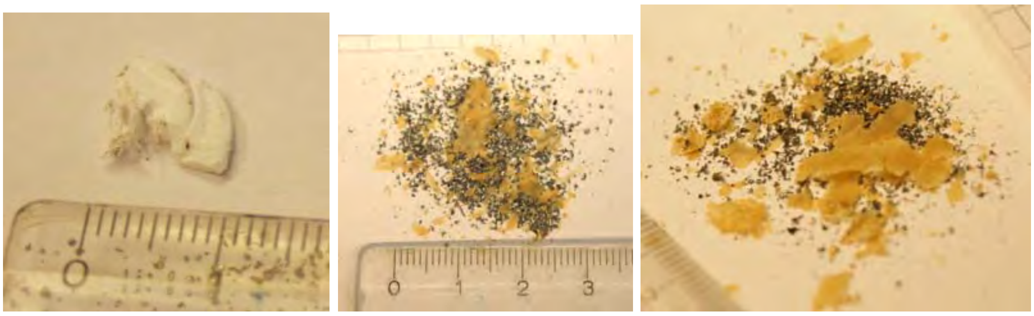


Figure 14: Images from flaws we found in the tubes. Left: Some kind of plastic chip, middle and right: dirt made from a kind of paper.

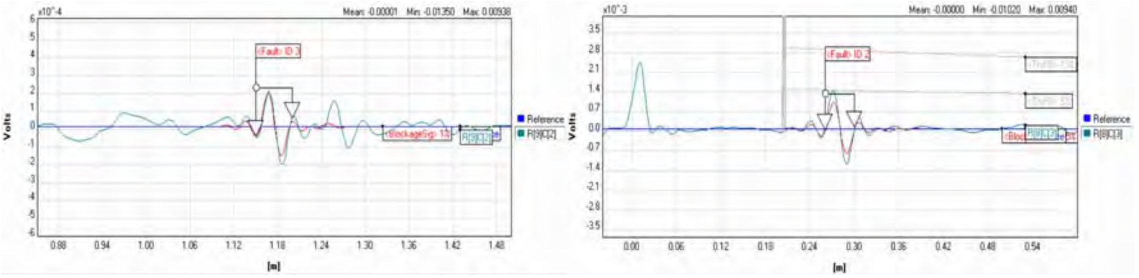


Figure 15: Left, signal of paper dirt, right: signal of the plastic chip.

5.2.3 Results group 3 (30 x 2 mm)

Here, three tubes contained burned-in oil and chips and two contained marks of mandrel breaks. As before, the burned-in flaws were not classified as defects, but led to a higher noise level. The two mandrel break marks could clearly be seen.
Furthermore, we again found some more unspecified flaws: One tube contained one large and several smaller chips, in another one we found something like a small stone. Finally, as in group 2, one tube contained paper-like dirt, mixed with small chips (see Figure 16). The APR signals of the chips and the stone are depicted in Figure 17; the signal of the dirt is similar to that from the dirt in group 2. One can observe that the large chip was positioned at about 0.38 m, whereas the smaller ones are distributed a few centimetres around it.

Figure 16: Non-specified flaws in group 3: Several chips, something like a small stone, paper-like dirt mixed with small chips.

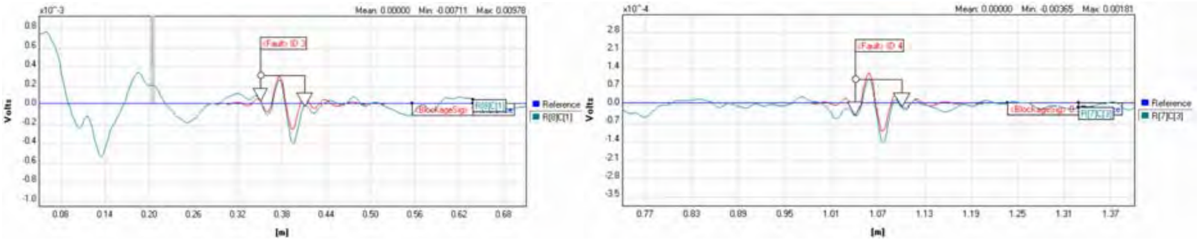


Figure 17: APR signals of the chips (left) and of the stone (right).

5.2.4 Results group 4 (25.4 x 2.96 mm)

In this group there were two tubes with burned-in oil and two with marks of a mandrel break. Just as before, the burned-in oil did not lead to an indication, but the two mandrel break marks could be found very clearly. In addition, as in group 2, we found some kind of plastic chip in a tube in which no flaw has been specified (see Figure 18).

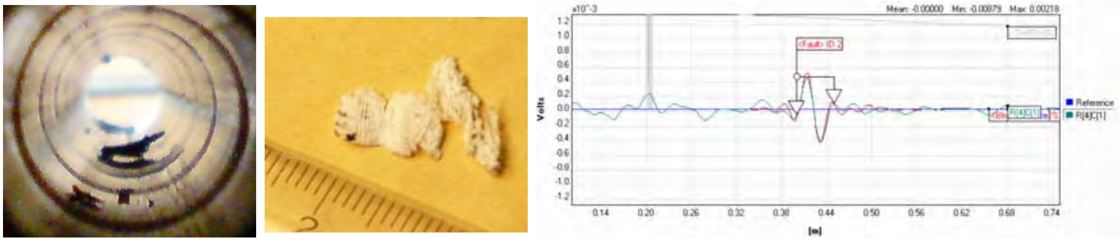


Figure 18: A plastic chip in the tube (left), outside (middle) and its APR signal.

5.2.5 Detection of specified flaws: Summary

The detection of burned-in oil and dirt turned out to be difficult. This kind of flaw can have an extent to several meters and does not exhibit an abrupt change in diameter. Instead, the inner cross-sectional area is decreasing continuously with an inner surface getting gradually rougher. The only chance of observing this seems to be a higher noise level if the inner tube surface is significantly rougher due to these flaws.

In contrast, the detection of the mandrel break marks worked very reliably. All-in-all we measured 10 tubes with these marks and in all groups all marks could be detected with a clear indication.

Furthermore, flaws that lead to an abrupt change in the inner cross-section, like the chips and the stone, seem to be reliably detectable, too. They have been found in several tubes which were marked as defect free by the manufacturer. Such defects will be analyzed further in the next section.

5.3 Performing measurements with artificial flaws

5.3.1 Description of artificial chips

To test the ability of finding chip-like flaws more systematically, we produced artificial chips in different sizes. With a long rod they can be inserted in the tube at well-defined positions. The exact dimensions of the chips are given in Table 2, the angle α (see Figure 19) was approximately 25° for all chips.

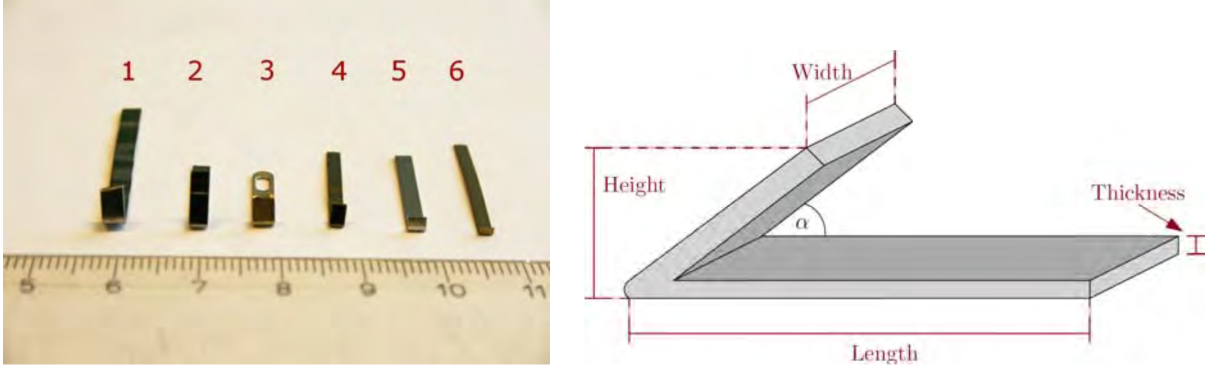


Figure 19: Left: Artificial chips in different sizes. Right: Nomenclature for dimensions.

The following table contains the exact geometric dimensions of the artificial chips.

Chip #	*1*	*2*	*3*	*4*	*5*	*6*
Width [mm]	3	2.5	3	2	2.5	2
Height [mm]	4.9	6.7	4	2.7	2	1
Thickness [mm]	0.5	0.3	0.3	0.2	0.3	0.2
Length [mm]	30	15.1	12	18.5	17.7	21.3
Cross-sectional area [mm^2]	14.7	16.75	12	5.4	5	2

Table 2: Sizes of the artificial chips.

In the following we describe which chips were inserted in which tubes and at which positions.

5.3.2 Group 1 (19.05 x 2.26 mm)

We started with the second largest chip (which is chip #1) in the group of smallest inner diameter (group 1, 19.05 x 2.26 mm). The nominal cross-sectional area of these tubes is 165.81 mm^2, i.e., the chip blockades an area of about 8.9 %. After calibration with five tubes in which we didn't find indications before, we inserted the chip at different positions in one tube. For this we used a long rod with meter marks (see Figure 20).

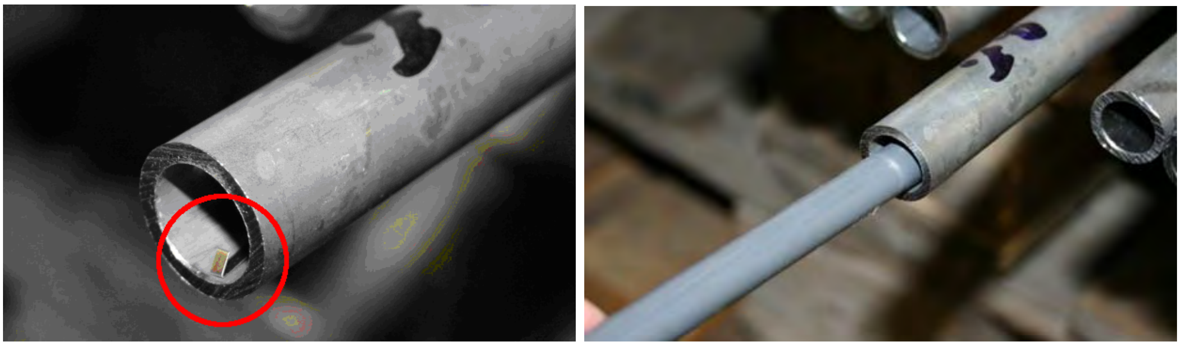


Figure 20: A chip is inserted into the tube and pushed with a long rod to specified positions.

We pushed the chip to the positions 1 m, 2 m… 6 m and took a measurement at each position. The chip could clearly be detected at all positions. Of course, the amplitude of the indications decreases with increasing distance, but the amplitude of the noise indications decreases as well. All in all, the signal to noise ratio did not change significantly (see Figure 21 for the indications of the chip in 1 m and 6 m distance).

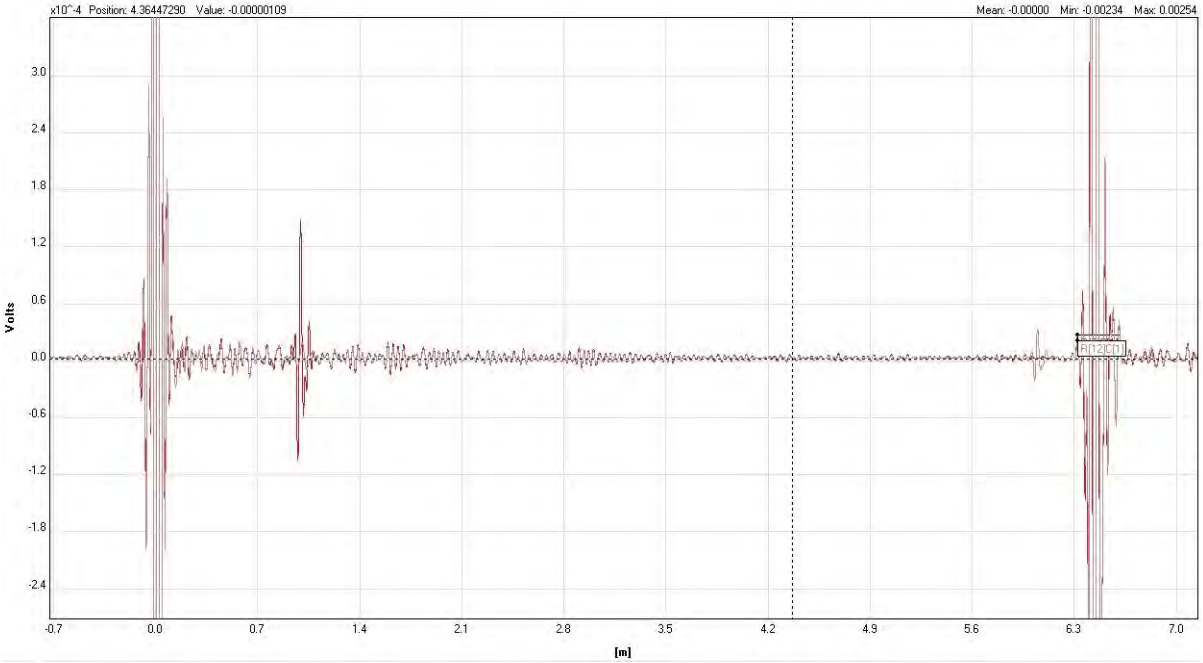


Figure 21: Measurements with indications at 1 m and 6 m. The amplitude of the signal is decreasing with increasing distance, but the noise is decreasing as well. The indication of the chip at 6 m is still clearly observable.

Afterwards we repeated the procedure at the same tube with a smaller chip (#4) which blocks an area of about 3.3 %. Again, the chip could clearly be detected at all six positions. Encouraged by these results, we directly switched to the smallest chip, which is #6. This blocks an area of only 1.2 %. We again achieved the same results – the chip could be detected at all six positions.

5.3.3 Group 3 (30 x 2 mm)

After the successful experiments with the chips in the tube of smallest inner diameter, we switched to the tubes with the largest inner diameter (group 3). Here, the nominal inner cross-sectional area is 530.93 mm^2. After calibration, we first started our experiments with the second largest chip (#1), which now blocks 2.7 % of the area. As before, it could clearly be detected at all six positions.

Finally, we inserted chip #4 in that tube. This now blocks only 1 % of the cross-sectional area. Again, it was possible to detect it in all six positions, but we observed that the signal to noise ratio was lower in the 1 m position than in the remaining positions. Possibly, there was some more dirt in this first region of the tube. However, after applying a band-pass filter, all signals were present very clearly as it can be seen in Figure 22.

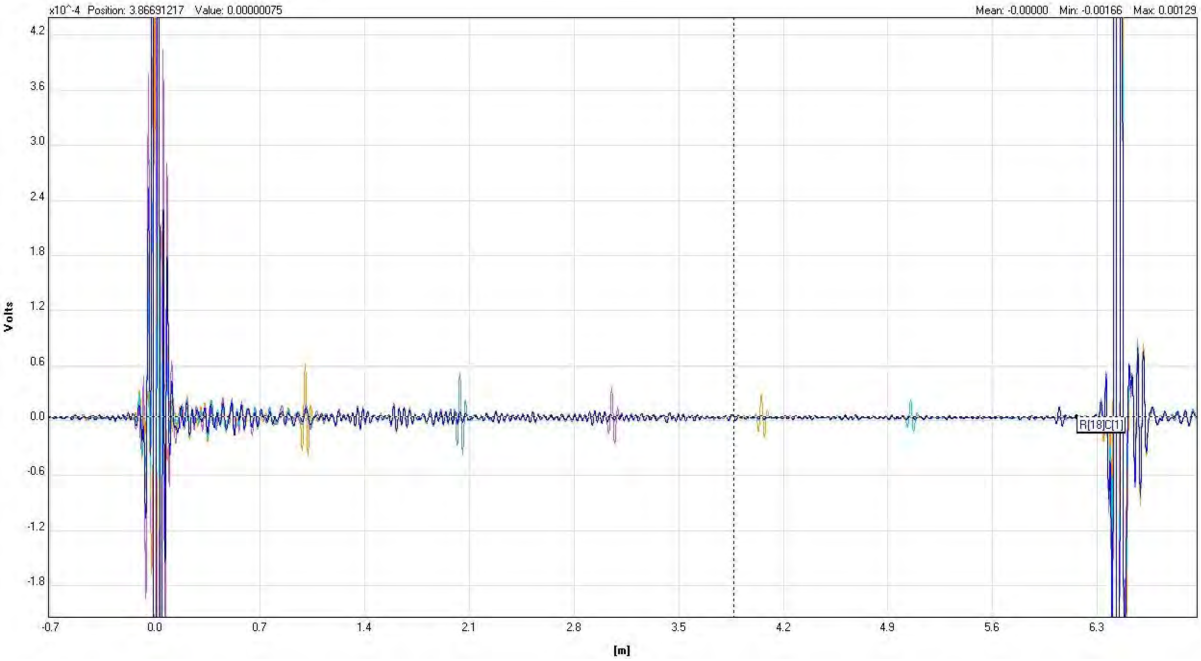


Figure 22: Signals of chip #4 in a tube of 30x2 mm dimension at positions 1 m, 2 m … 6 m. The indications are clearly visible at all six positions, even at 6 m distance. Again one can observe that the amplitude of the indications is decreasing but so does the amplitude of the noise – the signal to noise ratio does not change significantly.

5.3.4 Detection of artificial chips: Summary

The detection of artificial chips in these tubes was very reliable. As already expected from the result of the previous section, APR is able to find abrupt blockages very certain, even to a blockage size of 1 % of the inner cross-sectional area.

5.4 Length Measurement with an APR system

A possibly useful by-product of an APR measurement is a measurement of the tube length. As the sound velocity changes with the air temperature, the temperature (and also the kind of gas) in the tube inside must be known accurately, to get a really precise distance measurement. A wrong temperature will lead to distances which are too large or too small with an offset that does not vary very much, as the tube lengths are similar. In our trials we just specified a typical room temperature for the measurements without actually measuring it; hence, such offsets could occur.

To check the lengths determined from the APR measurements, we also measured the lengths of the tubes manually.

In Figure 23, the results of the APR lengths are compared to the manual measurements. For each group, the two curves have a very similar progress, but with an (anticipated) almost constant offset in between.

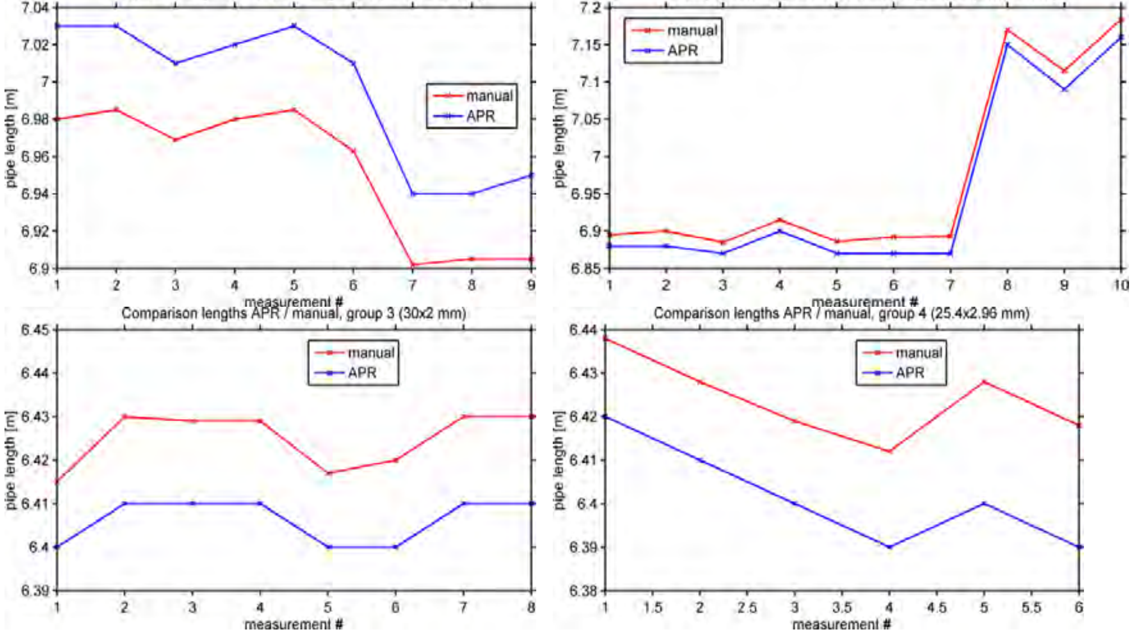


Figure 23: Comparison between the manual length measurement and the lengths extracted from the APR-measurements.

To better evaluate this constant offset, we have also plotted the differences of these curves (signed and absolute) in Figure 24. The absolute differences are between 1 cm and 3 cm for the groups 2-4. In group 1 the differences are significantly larger (approx. between 4 and 5 cm) and only in this group the manual measurements are smaller than the APR measurements. The reason, why this group differs so much is unknown.

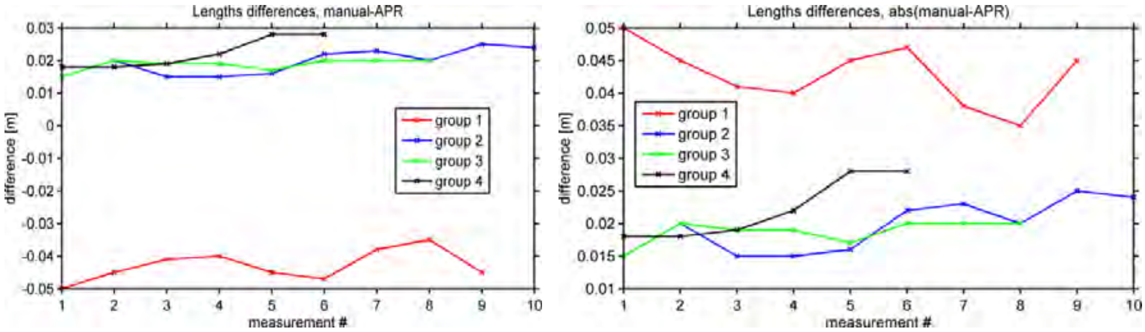


Figure 24: Signed (left) and absolute differences (right) between the manual measurement and the lengths extracted from the APR measurements.

All in all, APR shows a promising potential for length measurement of tubes. Except group 1, we already got length values that only deviate about 0.3 % of the real values - without an exact temperature measurement. Future experiments with precise temperature measurements could further explore the potential of length measurements of tubes with APR.

6 Summary/Conclusion

In this report, we dealt with two questions: Is it possible to apply the APR technology also to tubes with very small inner diameter? Can APR detect typical manufacturing defects (of course depending on the manufacturing process)?

The answer to the first question was not obviously “yes”, because it is not easy to insert an acoustic pulse with sufficient energy into a tube with such a small inner diameter. But the experiment showed that it is possible, although the maximum testable tube length is decreased in comparison to a tube with larger inner diameter. Moreover, one has to be aware of the fact that the adapter for the small tubes has still room for improvement. With a specially designed adapter the energy input will be higher, and the results better.

The question for typical manufacturing defects applies for both suppliers, but of course the kind of defects varies. In the case of MST tubes there are typically very small cracks inside the tubes. The volume of these defects is also very small and thus very hard to detect for the APR system.

Some chips, dirt and the felt plugs could be detected clearly by the Dolphin G3™. For these kinds of flaws the Dolphin G3™ is much more suitable than the UT testing. The artificial holes have been detected excellently even if they were located at the end of the tube.

The tubes of the second supplier (SMP) have the typical dimensions for APR inspection. Characteristic defects here are burned-in oil and dirt, grooves, chips and marks from mandrel breaks. Regarding the sample tubes that contain these defects, we were not able to find those elongated flaws that do not cause an abrupt change in the inner cross-section but only a slowly continuous one, like the burned-in oil and dirt and the grooves. If dirt changes the roughness of the inner surface significantly, it becomes noticeable by a higher noise-level. In future developments it could be possible to classify these signals also as defect indications.

In contrast, the flaws like chips and mandrel break marks were very reliably detectable. They cause an abrupt change in the cross-section and give a clear indication in the measured signal. The trials with the artificial chips show, that the Dolphin G3™ from AcousticEye can still reliably find chips with an area of 1 % of the inner cross-sectional area of the tube.

Comparisons of tube lengths determined by APR with manually measured lengths already provide promising results although the precise temperature was not known. The potential of APR for length measurement should be explored in further investigations.

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