ULTRASONIC PIG DETECTION AT PIPELINES

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Abstract

The contribution deals with the application of new pig signalling techniques on the basis of ultrasonic probes and methods. It will be shown, that ultrasonic techniques are extremely versatile in order to work under different operational conditions and can be adapted to very different situations. Especially, the possibilities are explainded and exemplified which arise for pigging campaigns at gas pipelines. Two principal approaches will be discussed and combined. First, ultrasound can be sent actively into materials. It can be influcend by changes of the system. This information can be read out by the received ultrasonic pulses. Second, many technical systems, such as pipelines and moving pigs, produce a lot of valuable noise which can be exploited for pig signalling.

Introduction

It is known that acoustic and ultrasonic techniques can be used for several tasks in the pigging technologies and industries. Some papers have been presented on the PPSA workshop in the last years. Highlights have been the impressive developments in the field of intelligent pigging and data evaluation. This provides a drastic improvement for pipeline saftety and integrity as well.

Measurement methods basing on the use of ultrasonic sensors are increasingly used for industrial fields such as pipeline integrity and maintaince, for non-destructive testing tasks at pipelines and constructions. In a similar manner, ultrasonic sensors and techniques are very valuable for the supervision of processes, pigging campaigns and transportation processes. Even the on-field and in-process characterization of fluids and materials can be realized. The number of possible applications is still increasing for several reasons.

In order to give an impression of the flexibility of the ultrasonic measurement and testing technology a short survey is given at the beginning.

Some of the applications and industrial services should be of direct interest for the pipeline industry and maintaince and for the pigging branch as well. Ultrasonic testing is used for leak detection (which directly saves money for compressed air systems) and for bearing diagnostic devices. Ultrasound is heavily used for wall thickness measurements (uncoated and coated walls, ranging from µm ...m).

An important advantage of ultrasonic techniques comes from the ability to measure (non-intrusive) "through the wall“ which is an important non-contact technique in process control (e.g. for level measurements).

The physical basics of the applicability and adaptibility can be found in the often very different material dependencies (note: acoustic waves are mechanical ones) of the sound velocity, of the attentuation of travelling waves and of dispersion effects (dependence on the frequency), which can be used in order to apply spectroscopic techniques:

For the overview, only a few (apparently simple) formulae should be given as a reminder. It should be noted that these are only simplified notations. However, they are very valuable for a rough estimation of dimensions, path lengths, possible resolutions and the order of the effects. Especially in solids, the physics can become fairly complex. The sound velocity can be obtained from the product of the wavelength and the frequency,

$$c = \lambda \cdot f$$

The attenuation of a travelling wave in a medium can be written as

$$I = I_0 \; e^{-\alpha x}$$

where α is the absorption coefficient and *x* is the length of the sound path. Frequencies of 20 kHz up to some ten MHz can be applied and are commonly used. The following overview is intented to survey possibilities for the application of ultrasonic sensors and techniques.

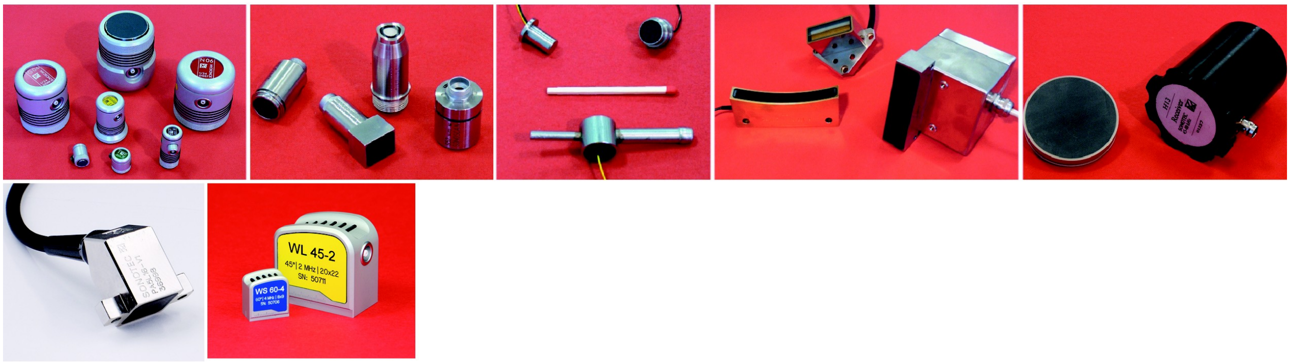
Applications in Pipeline Industry and Service (selection)

- ***active pulse methods***
  → liquid level estimation
  → recognition of different liquids
  → measurement of wall thickness
  → level limits
  → inspection and monitoring of sedimentation and deposits
  → measurement of the accumulation of sand, debris, incrustation in tanks, pipelines, barrels
  → advanced NDT[1]-tasks (e.g. "intelligent“ pigging, material testing)

- ***passive sound emission methods***
  → acoustic detection of moving sand in pipelines
  → amount of debris
  → condensate inspection (e.g. in valves and traps)
  → detection of leakages
  → flowing sand and debris in pipelines
  → monitoring of materials and constructions

Ultrasonic Sensors and Probes

One important key for an optimal application of the ultrasonic technologies and the complete exploitation of their huge and versatile potential is caused by the great variety of available sensors. An adapted sensor solution and probe construction can be found for almost any problem. An impression is given by figure 1 which shows some sensors developed and sold by SONOTEC.



Figures 1. Examples of industrial sensors –
from left: contact technique probes, immersion probes, miniatur probes, multi-channel probes, low frequency probes, phased-array probe, angle transmitter-receiver probes

Two typical examples stand for the application of ultrasonic sensor technologies in many branches of industry. The working principle - the non-intrusive measurement through a wall - stands (amongst others) for an important advantage of the method. Many variations can be derived.

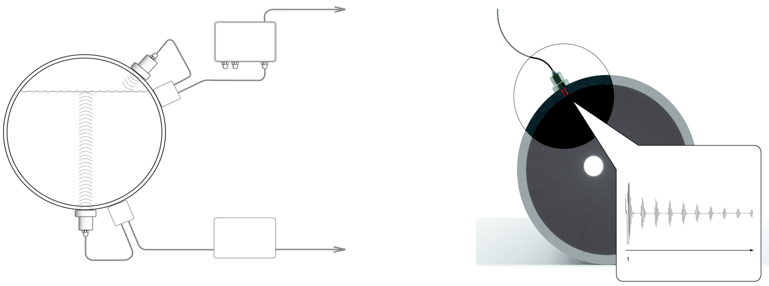


Figure 2. Measurement through the wall – a typical advantage for ultrasonic measurements.
Left: level control of liquids (travel time and intensity are used for the estimation of filling heights or for the control of defined filling levels, right: measurement of wall thickness (travel time of the echoe(s) of a transmitted pulse)

[1] NDT - Non destructive Testing

Experimental Approaches and Technical Solutions for Pig Signalling

Pipeline Monitoring and Pig Location for Crude Oil Pipelines

A method of ultrasonic pig signalling for oil pipelines has been developed by SONOTEC [Son08].

The method works like a photoelectric guard. An ultrasonic signal is permanently sent through the pipeline. A part of the signal will be reflected by the back wall and then received (this is possible for the combination of steel walls and oil, see next chapter). When a pig comes to pass the position of the probe, it decelerates or prevents the reflection. The principle is explained by means of figure 3. An extension of the method and the commercial probe (optional) enables the recognition of different products if the sound velocities of this products differ. Caused by the physical principles described above, some commercial and operational advantages of the use of ultrasonic technology are obvious. It can be easily installed in non-intrusive clamp-on technology which does not require any process interruption. The pipeline will not be affected due to the non-contact character of the measurement. Experimental attempts have been done for gas pipelines too. It is known, that pinging of ultrasound through the wall into the gas can succeed for high pressure. However, a certain minimum pressure must be guaranteed.

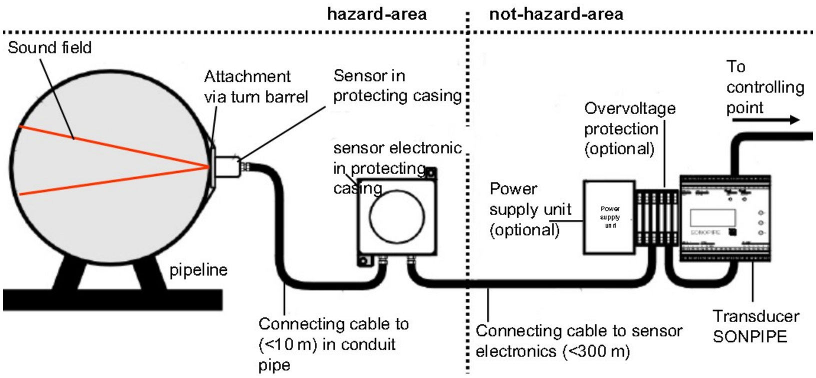


Figure 3. Standard configuration of a transmitting ultrasonic probe for the application at crude oil pipelines

Pig Signalling Methods for Gas Pipelines

The technology for liquid pipelines cannot be simply transferred for gas filled pipelines for physical reasons which are outlined below. It is well known in the PPSA community that there is great variety for pigs with respect to construction, weight, diameter, sensor instrumentation, pricing and so on. Cleaning pigs, caliper pigs, intelligent pigs will provide new demanding tasks for pig signalling in gas pipelines. Furthermore, different pipeline diameters, different gas pressures, different scenarios of pigging (pig velocity, stop and run), the existence of uncoated and coated pipelines (Cor06) make the situation complicated for operators and service as well.

Pig Detection by a Non-intrusive Active Method

The use of the direct signal path of acoustic pinging through the steel walls of a pipeline is complicated or even almost completey prevented by the reflection properties of the involved materials and fluids. This can be understood by a look on the effectivity of the reflection or transmission of an acoustic wave through the wall-gas-system.

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

R is the reflection coefficient, where Z_1 and Z_2 denote the impedances of the materials (e. g. steel and natural gas). The impedance Z results from the product of the sound velocity and density.

Having a closer look on real material numbers, it becomes clear that a "simple" pinging method (similarly as for oil filled pipelines) cannot be applied. A crucial point for the application of ultrasonic methods is caused by the reflection properties of acoustic waves when moving from steel (or other wall material) to the gas medium and vice versa.

material	*density (kgm^{-3})*	*sound velocity (ms^{-1})*	*impedance (kgm^{-2}s^{-1})*
steel	7850	5920	$3.92 \cdot 10^7$
water	1000	1484	$1.48 \cdot 10^6$
air (1 bar)	1.204	343	$4.13 \cdot 10^2$

Table 1: Impedance of common materials

The situation can be examplified by means of a typical material combination. According to table 1, the transition from steel to air at 5 bar exhibits a transmission effectivity of about 0.01%. That means, 99.99% of the intensity of an incident sound wave is reflected. Taking into account the surrounding air (1 bar), a second reflection will occur with R~99.998%.

By means of a contact sensor in an optimized angle, a sound pulse can be sent into the pipeline wall. The high degree of reflectivity enables a multi-reflection path of the ultrasonic wave. As shown in the sketch of fig. 4, the read out of the sound wave will be done by means of a second ultrasonic probe (receiver). The magnitude of the received intensity depends on the relationship, as mentioned above, of the impedances of the materials. In contrast to the low attenuation of the sound wave in case of a gas-metal interface, the situation is changed when a pig passes the sensor of the radially arranged dual-probe.

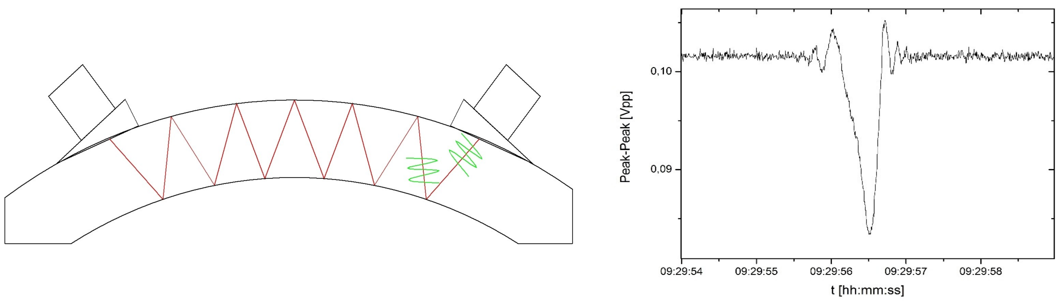


Figure 4: Principle of the pig signalling by means of the damping method.
The ultrasonic pulse is sent by probe 1 into the wall of the pipeline. The probes are radially arranged on the circumference. Many reflections occur in the steel wall of the pipeline due to the huge differences in the impedences of gas and wall. A remarkable attenuation will be induced in the moment when the pig passes the sensors. The reason is the higher impedence of the polymeric disc material. The ultrasonic wave can be transferred much more effectively into the sealing polymer disc. The scan on the right demonstrates the effect under laboratory conditions (one disc only). The curve represents the intensity of the received signal (at probe 2) which suddenly drops down due to the passing disc.

The impedance of the polymeric material of front and rear sealing discs is much higher than the impedance of the gas. That means, that a greater part of the sound energy can cross-over into the disc material of the pig. The lower degree of the reflection results in a higher attenuation of the signal.

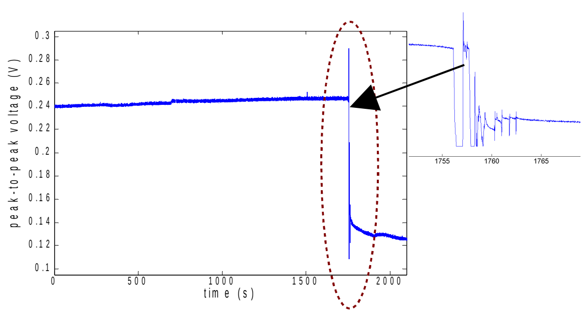


Figure 5. The use of ultrasonic attenuation methods on field operation (for a cleaning pig run).
The baseline is also affected since the inner side of the wall has been influenced by residual oil collected by the pig in that pipeline. The zoom reveals the resolved signals of the discs of that pig.

The alert information arises from the comparison between the two damping situations (metal-gas / metal-disc). The method has been recently patented.

Sound Emission as Pig Signalling Tool

The motion of pigs in pipelines depends on severals factors. There is a great variety of existing pigs, which produces different patterns of sound (with respect to frequency, intensity, time behaviour) due to differences in their constructions and operational conditions in different pipelines. That means, that pig detectors must be able to deal with cleaning, caliper and intelligent pigs as well. A reliable and intermediate interpretation of acoustically induced signals at suitable sensors must be enabled for a great bandwidth of technical situations, unpredictable scenarios of the pig motion and distortions. Pigs can run and stop under very different driving pressures with very different speeds [HosS07]. These moving scenarios can be hardly prognosed. We can find only very few papers dealing with the use of sound emission in the pipeline and pigging engineering science - despite of their great potential. Attempts and proposals have been made to use the physical effect of sound emission as a passive detection method (Bro96, Bro97).

The Problem

Mechanical excitations (scratching, pulse by a hammer ….) can be the source of acoustic waves which travel in all directions through the pipeline. Assuming a sound speed of 6 kms^{-1}(longitudinal waves in steel), the wave needs about 1 ms for a distance of 6 m. When observed at different sensors, a time lag occurs

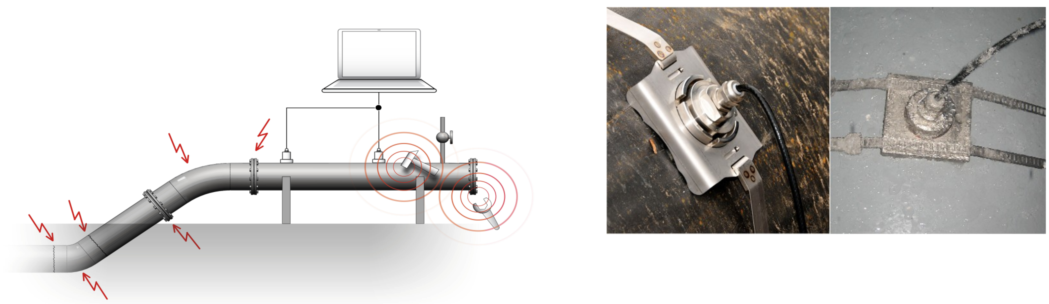


Figure 6. left - Schematic sketch of a typical situation at pig receiver trap of a gas pipeline. The dual sensor arrangement is explained in the text below. The sensors are axially arranged (in contrast to the "active" method described above).The left probe can be understood as sensor 1 in the given data examples and the right one as sensor 2. Right – Typical sensor installations (for permanent operation or for temporary service) at a pipeline. Sensors and methods are robust and insensitive with respect to snow, rain and other environmental influences .

This delay can be numerically extracted by correlation techniques. The example in figure 7 demonstrates this effect. Using such techniques, it would be possible (in principle) to differ between signals arising from the "left" side or from the "right" side of a sensor. A valuable tool for a pigging passage could be proposed. However, under practical conditions, the typical noisy broadband excitation prevents the resolution of "single" correlation events. With the same argument, the use of Doppler-Shift fails in practice. It could be shown that the frequeny shift occours under very optimized laboratory conditions when a model source changes the motion relatively to a probe. The practical use is not realistic when there are no moving acoustic sources with specific frequencies.

The data presented in this contribution have been collected at pipelines with diameters from 500 up to 900 mm. However, the are no limitations for the application to smaller and larger tube diameters.

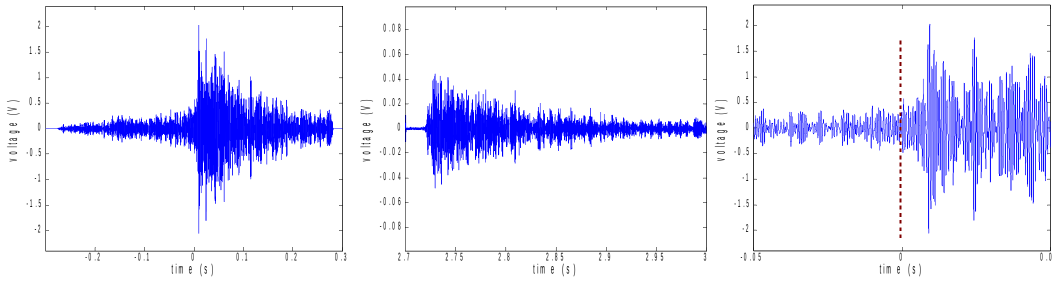


Figure 7. Correlation of an acoustic signal (excitation by means of a (low intensity) hammer pulse at sensor 1, sensor 2 in distance of about 10 m). The dashed line illustrates the lag of the shift.

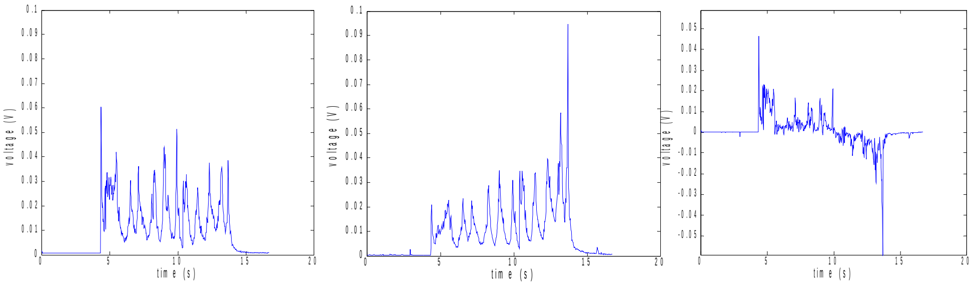


Figure 8. Laboratory test simulation of a pig motion between two acoustic sensors (sensor distance about 10 m), from left: signal (r.m.s.) at the first sensor and at the second one (middle), difference signal (right). No ultrasonic filtering has been applied. About ten crossings of the welding seams excite acoustic signals. The relative change of the signals is the source for the algorithm which decides on a pig passage. It is obvious, that complicated signal patterns can occur – depending on the construction and operation.

Spectral Behaviour of Pipeline Noise

For a correct interpretation of the results and for the design of robust algorithms, it is necessary to have a deeper look on the spectral behaviour. As mentioned above, there are no special (narrow frequency band) spectral features (such as Eigenmodes) which can be assigned to the motion of a certain type of a pig. The spectrum comes always from a superposition of different noise sources (pipeline vibrations, flow noise, friction of the pig at the wall, contact to welding joints and other).

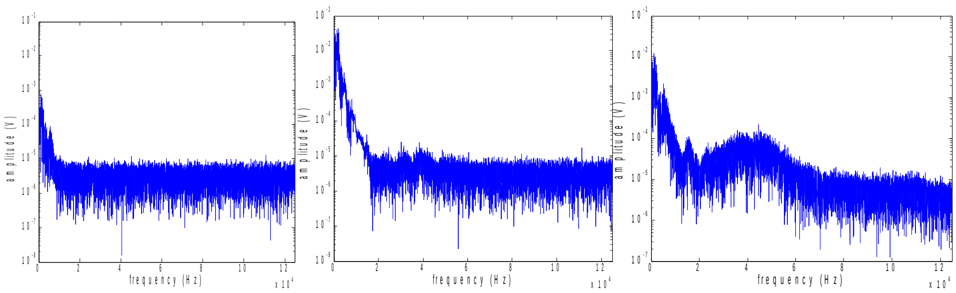


Figure 9 . Frequency characteristics (typically averaged over 5 s intervals) of noise during a pig run in a (gas transportation) pipeline, from left: gas flow only, additional unknown mechanical sources of noise (e. g. from service work), friction noise of a passing pig. The clearly enhanced signal part at ultrasonic frequencies is obvious when a moving pig passes the sensor position.

The following set of figures demonstrates the complexity of the physical and technical situations and scenarios during pigging runs and illustrates the basic ideas of the sound emission approach.

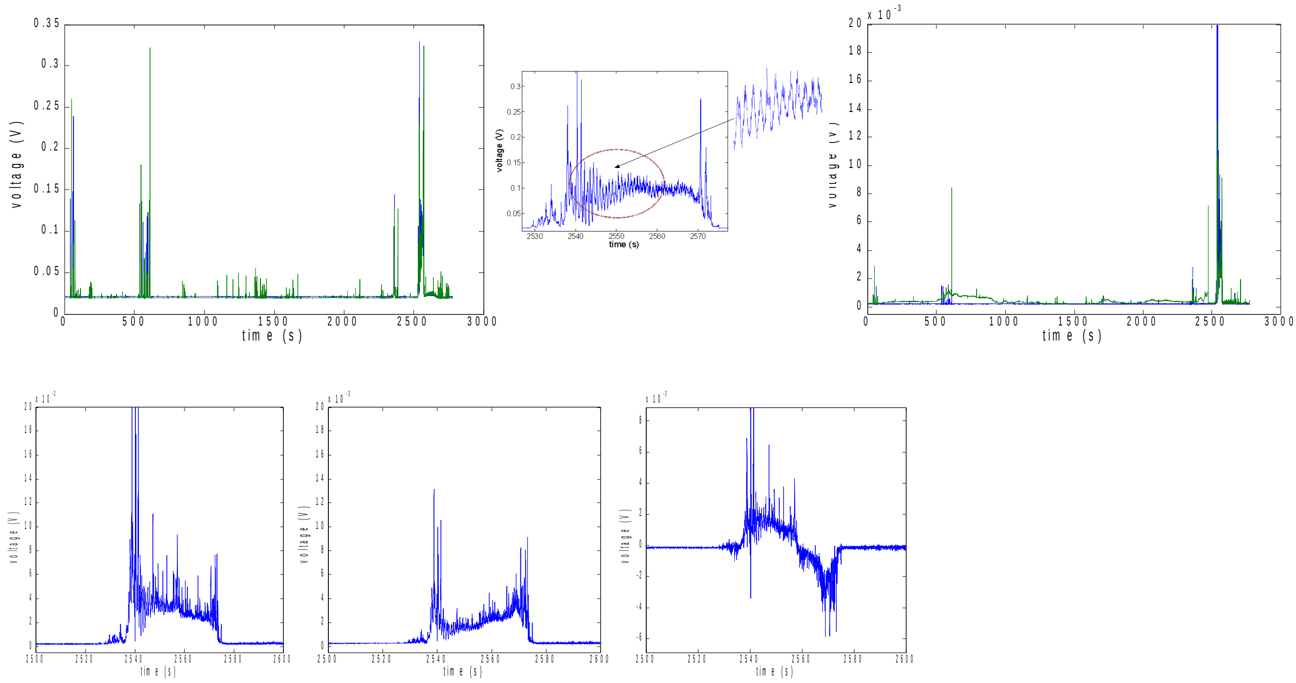


Figure 10: top - Long time recording of the acoustic signals (cleaning pig, 900 mm pipeline diameter, uncoated) received at the sensors 1 and 2 – left: r.m.s. (root mean square) signal without filtering,
middle: the pig passage (unfiltered) at sensor 1. This signal in the proximity of the pig receiver results from a fairly complicated motion. There is no smooth travel of the pig. It moves rather in a stick-slip-procedure which makes it impossible to use a “simple” level indicator as an alarm for a passage.
Top right – the same recording but re-calculated with a filter for ultrasonic frequencies. Consequently, the intensity is drastically reduced but still sufficient. Furthermore, “long range” distortions can be eliminated more effectively by means of simpler algorithms.
Bottom: The digitally r.m.s. filtered signals (20 ...60 kHz) of the passing pig at sensor 1 (left) and 2 (middle). The difference (right) signal (which is the source for the alarm) is fed into an integration algorithm.

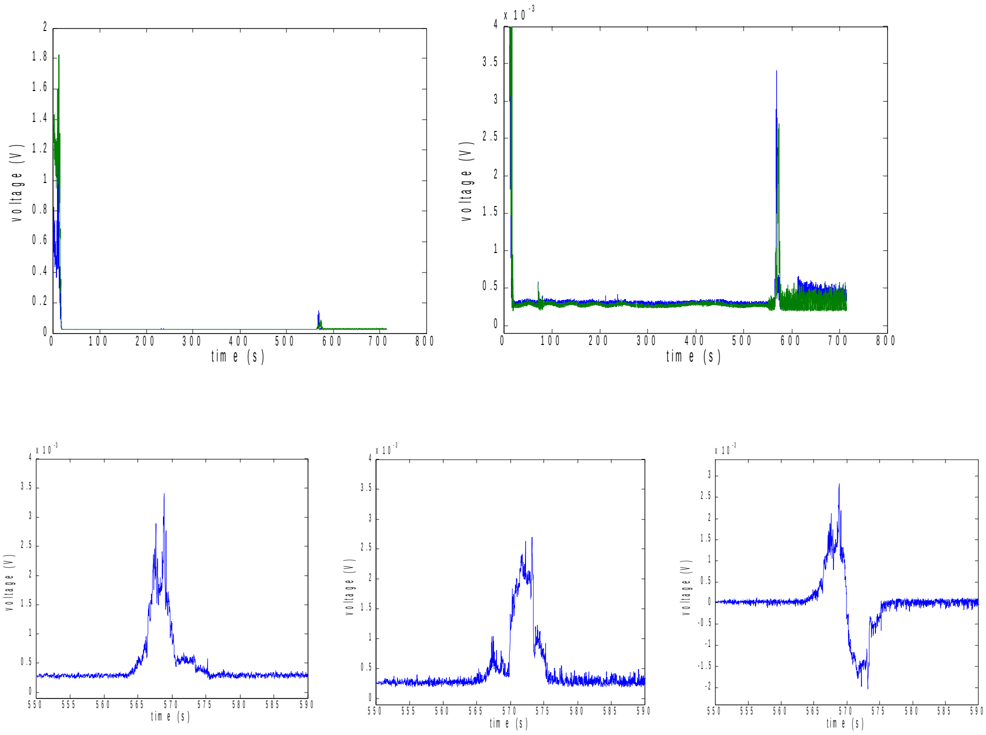


Figure 11: Acoustic emission (the same notation as in figure 10) for a further pipeline pigging campaign (cleaning pig, 500 mm diameter). Different signals and intensities originate from differences in coating, speed, amount of debris, pig construction, pig receicer arrangement, different driving pressure regime and so on. Here, the low signal comes from fewer debris “as usual” and reduced friction caused by oil coating of the inner tube walls. Note, the event of pig passage is identical with that of figure 5.

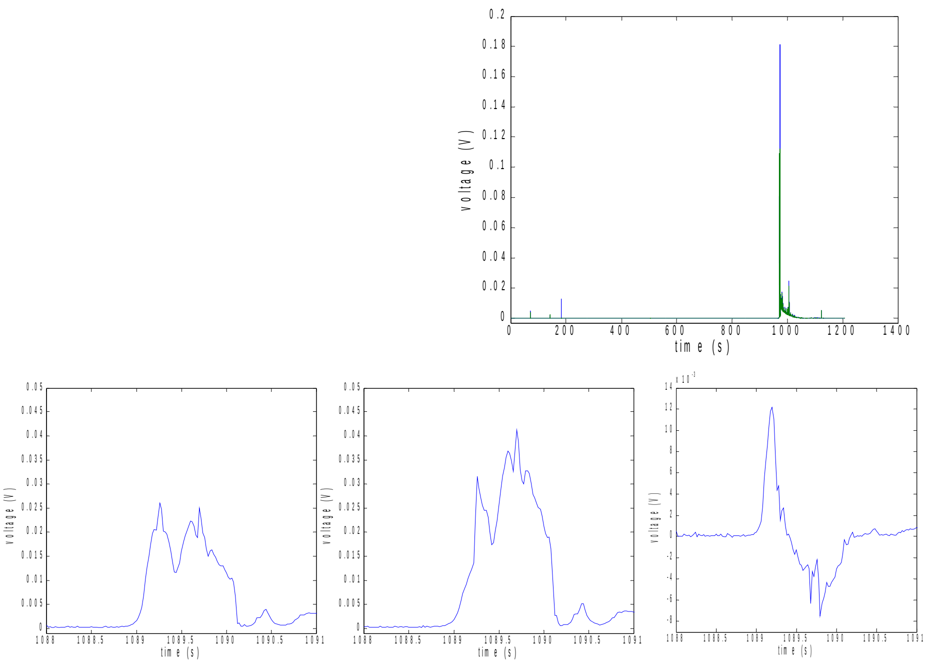


Figure 12: A further example of a cleaning pig run. The ultrasonic signal is given only. Note, that the difference r.m.s. signal trace is calculated with normalized intensities of the two probes.

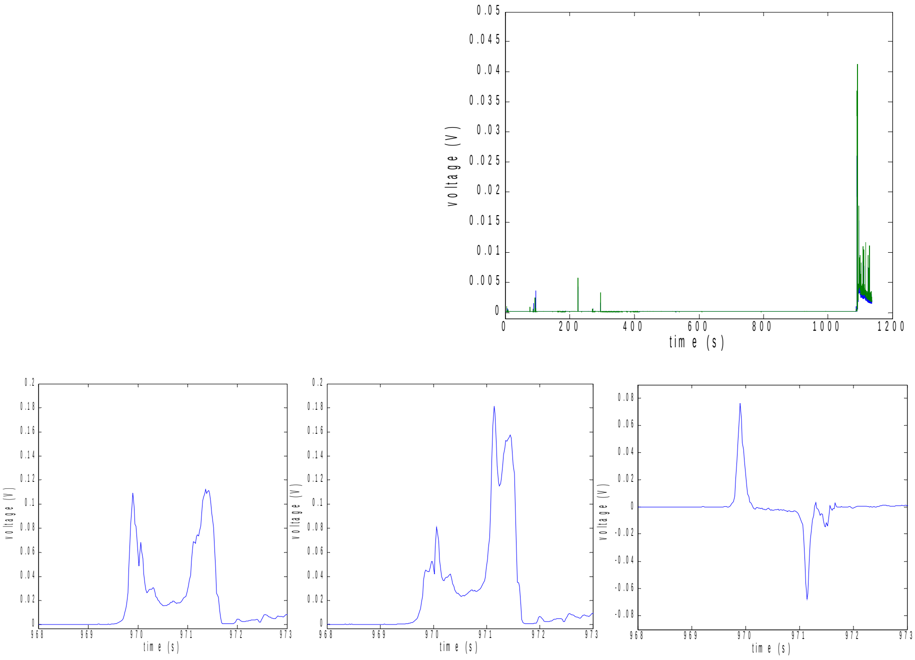


Figure 13: Repeated pigging at the same pipeline as shown in figure 12 (cleaning pig, ultrasonic filter). The used pig carried brushes which are a source of intense ultrasonic excitation. Consequently, the intensity of the signal is higher (compared to fig. 12) when the pig is moving at similar speed. The ultrasound level is clearly higher.

Noise (from gas flow, service work, high intensity pulses from contacts of a moving pig with welding joints) can complicate or prevent the interpretation of the "real“ acoustic pattern of a pig passage at the position of the acoustic probes. Therefore, the "wrong“ or "unwished“ signal contributions must be distinguished from the "passing“ signal. It should be mentioned that the "distortion“ intensity can be (much) higher than the "wanted“ signal (e.g. see fig.12). It is essential that the discrimination of such signals can be done automatically even if the probes exhibit no identic sensitivities. As an example, the result for accidental pulse excitation (the pig passes a "welding joint“ or working noise from a far distance occured) is given.

The sound emission sensor technique has been patented as well.

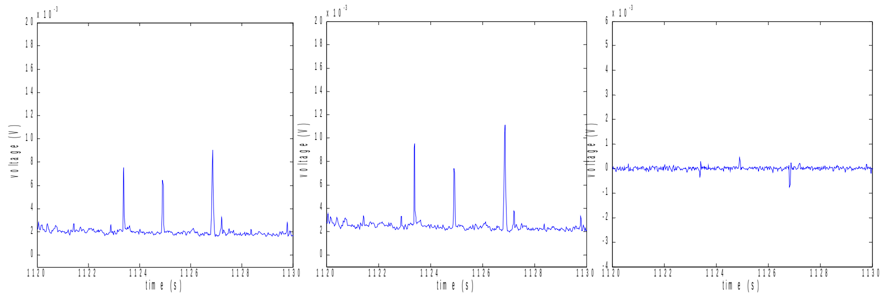


Figure 14: Elimination of distortions by calibration of probes and choosing the “right” integration time. Signals from distant sources (even with complicate signal patterns) can be easily removed by suitable filters or algorithms. The distortions of other noisy sources such as rain can be suppressed, too.

Role of Algorithms

Some basic elements of the algorithms are summarized:

The sound emission signals of (at least) two probes (which have an optimum distance) are used in real-time.

The signal is filtered for ultrasonic frequencies (e.g- 20...60 kHz) in order to suppress signals from modal vibrations, operationally induced vibrations and stochastic low frequency noise.

The signal is averaged (in the order of milliseconds - according to the necessary resolution). Amongst the use of the r.m.s.-data of the measured signal, spectral features such as Fourier spectra or wavelets can be used for further improvements and more sophisticated treatments of the time characteristics of the signals.

Small variations due to stochastic effects or different running speeds of the pig can be smoothed by digital filtering (using adaptive filter lengths).

The key information for measuring and calculating a *safe* and *reliable* alert comes from the comparison of the two channels. As shown in the examples, a change of the sign occurs as a result of a suitable difference procedure.

Combination of Methods

A great number of pigging operations must be analyzed for the development of stable and robust algorithms. A demanding amount of data space (if uncompressed - up to 50 GByte per run) were aquired at high sampling rates, stored and re-analyzed with different algorithmic approaches. The aim was to obtain optimized algorithms which can be used under the conditions of field operation for any kind of pigging campaign.

The new probe arrangements result in improved pig signalling equipment and new opportunities for service.

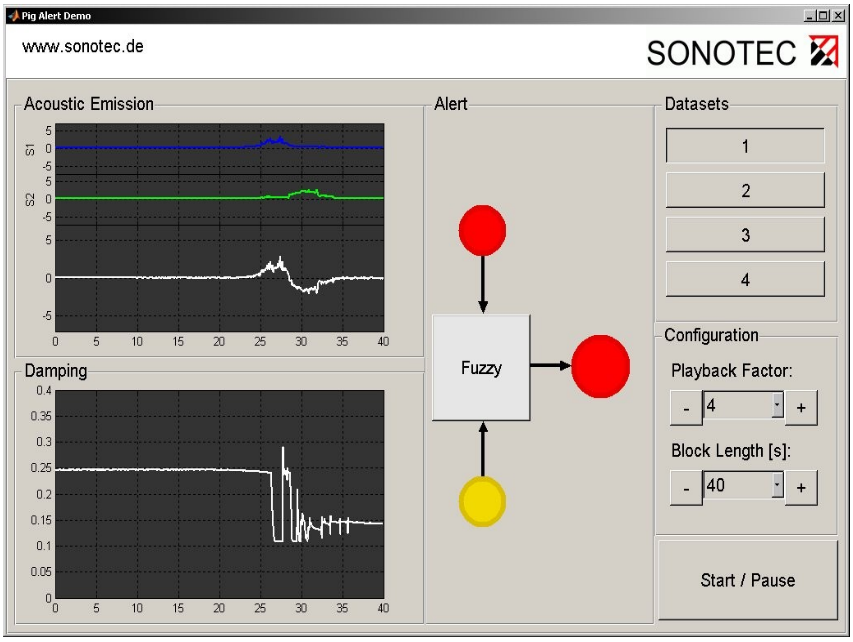


Figure 15: Screenshot of the online-service program for the pig alert. The data windows stand for two independent sensor pairs representing the (“active” and “passive”) methods described in the text. Each of the methods is able to produce an alert. However, the reliability of pig signalling can be increased by the combination of the methods. The link-up can be done by various logical (and/or/.../fuzzy) operations.

The demonstration (fig. 15) will run at the conference exhibition.

Conclusion

It has been demonstrated that acoustical technologies are powerful and versatile for the application in pig detetion and signalling. The contribution was aimed to the explaination of some relatively new applications of ultrasonic methods for pig detection purposes. The robust and flexible methods work without any *a priori* knowledge about the type of the pig and the operational conditions. Ultrasound is harmless and does not influence the operation and the environment.

The presented techniques enable the detection of pig passages in flexible clamp-on procedures with a high reliability. A further improvement of the results and of the reliability can be achieved by a combination of different acoustical techniques. The technique and procedures can be adapted to a broad range of practical situations.The progress in sensor development and measurement methods, the increase of *onboard* calculation power and new algorithms will be a source of improved and extented acoustic and ultrasonic methods as demonstrated for the pig signalling in gas pipelines. Furthermore, the method carries the potential to be extended to pig localization. We believe, that the potential of the use of ultrasonic techniques is still underestimated in the pipeline and pigging sector as well.

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