Ultrasonic Measurement Techniques in Gas Pipeline Inspection – A Case Study

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Abstract

Ultrasonic measurement techniques as applied in inspection devices such as pigs are frequently used for the assessment of oil pipeline integrity. Since a liquid coupling medium (e.g. water) between the detection device and the pipe wall is required, this technique is however not directly applicable to a gas pipeline. This leaves two options: a short water batch propelled by pressurised air and the use of a half batch, which means the pipeline is completely filled with water during inspection and must then be dewatered again during a second pig run.

In the case study presented here, a short batch run was not feasible since this approach was found to lead to unacceptably high pig velocities due to occasional steep declines of the pipeline in question. The half batch approach chosen for this reason, however, required detailed preparatory modelling of the resulting hydrostatic pressures to avoid both overpressures and water hammer effects during the pig run due to the large differences in elevation of several hundred meters. It also presented new practical challenges such as the management of large amounts of water and the requirement for high internal pressures during the pig runs. An overview of the inspection carried out is given, with an emphasis on the solutions developed and implemented to address these aspects.
1 Introduction

Ultrasonic (US) measurement techniques are commonly used for intelligent pigging of oil pipelines. However, this principle requires that the contact between sensors and pipe wall be established through an incompressible medium. For the integrity assessment of gas pipelines, the US device therefore has to travel in a liquid body created for this purpose, e.g. made of water.

In the case studied here, a gas pipeline with the elevation profile shown in figure 1 was to be inspected with an US device. The project was carried out in summer/fall 2011 to ensure availability of the pipeline during the winter months and to avoid the handling of large amounts of water at low ambient temperatures.

![Figure 1: height profile of the pipeline to be inspected](image)

Pig launchers were available at the locations A, B and C. While that would have enabled separate pigging of the sections A-B and B-C, no sufficient amounts of water were available at B and C, which led to the decision to inspect both sections within the same project.

There are two options for US pigging:

1. A batch run
2. A half-batch run

For a batch run (figure 2), the US device is enclosed in a body of water enclosed between disk pigs on both the front and rear end. The batch is propelled by compressed air.
For a **half batch run** (figure 3), the batch is built up in the same fashion, but is then propelled by pumping water into the pipeline. Consequently, the pipeline will be completely filled with water when the pig has reached its destination and must later be dewatered using air compressors.

While for a half-batch the amount of water required is simply the pipeline volume, the length of the batch is subject to optimisation. A longer batch, by increased batch friction, will dampen the velocity fluctuations that will result from the given slopes during the batch run and thus lead to lower velocities, but it will also require more effort for the subsequent treatment of the batch water.

The inspection time and the associated costs are higher for a half-batch run because the pipeline must be dewatered in a second half-batch run. For the height profile considered here the average pig velocities are similar for both approaches. This is also the case for other pipeline diameters since the average velocities of batch and half-batch runs are determined by the air and water supply, respectively. However, smaller pipelines also result in lower peak velocities for batches due to the higher ratio of friction forces to batch mass.

For a half-batch, the velocity is directly controlled through the water mass flow delivered by the pumps. During dewatering, it may be constrained by either the admissible mass flow through the water treatment plant or the capacity of the compressors during times of pressure buildup.
For a batch run, the velocity depends on numerous parameters such as the slope of the pipeline and the friction forces acting on the pigs and the water body whose impact can be assessed, but which can hardly be influenced. The only variable parameters to have a marked effect are the batch length and the pressures before and behind the batch, but these also only provide some limited degree of control of the peak velocities.

A batch run can be carried out by keeping the pressure before the batch constant through venting and providing a constant air mass flow from behind. Since the batch is short compared to the total pipeline length, the height difference between front and rear end will be small except on extremely steep inclines exceeding the batch length. This means the hydrostatics will not give rise to a rear end pressure close to the maximum permissible value as long as the front end pressure is not chosen unduly high. The shortness of the batch also ensures that this holds true while it crosses a valley and that the pressure in front can be chosen sufficiently high to prevent the pressure in the batch from falling below the saturation pressure of the liquid when crossing a mountaintop. In the latter case the batch could separate which can lead to a water hammer when the parts join again. In short, for a batch run it is relatively straightforward to define operation parameters that ensure the pipeline is not damaged during inspection.

For a half-batch, avoiding these scenarios requires careful variation of the air pressure in the pipeline. This will be described in detail below.

Table 1 summarises this general comparison of the two methods.

<table>
<thead>
<tr>
<th></th>
<th>Batch Run</th>
<th>Half-Batch Run</th>
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<tbody>
<tr>
<td>Amount of water required</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Inspection time required</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Ease of velocity control</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Ease of pressure control</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Based on these general considerations, a batch run is preferable to a half-batch run. This option was therefore investigated first.

### 2 Batch Simulation

The prediction of the batch velocities requires a numerical simulation based on a force balance on the batch taking into account the pressures before and behind the batch as well as gravitational and frictional forces (figure 4). The given height profile is taken into account in a coefficient in the ordinary differential equation derived from the balance.
The software developed in-house to perform this simulation was validated using velocity measurements made during previous inspection projects involving a batch of 600 m length (figure 5).
The comparison shows occasional underpredictions of the velocity at simulation results above 10 m/s, which may be due to measurement errors, the use of a simplified height profile leading to peak velocities being averaged out or the local variation of frictional properties. The overall agreement is satisfactory, however, and the fact that this effect is borne out only at velocities that are prohibitively high for the purposes discussed here (see below) bodes well for practical applications.

Figure 6 shows the batch velocity on section A-B obtained for a 5,000 m long batch and a grossly exaggerated total pig friction of 12 bar. Although both these numbers represent optimistic assumptions, the velocities reach values up to 8 m/s during steep declines, which well exceeds the limit of 3 m/s determined for the case at hand based on the specifications of the US scanner. The pipe sections in question are marked in red in figures 6-10. The flow friction was modelled to be proportional to the square of the flow velocity.

Figure 6: velocity distribution on section A-B for a 5,000 m batch with assumed pig friction forces equivalent to 12 bar

For the inspection of the second section a batch run from C to B was assumed because it led to lower peak velocities than from B to C (figure 7). However, even in this case velocities as high as 9 m/s are reached.
The figures 8-10 show variations of the batch length and pig friction for section C-B in order to illustrate the degree to which the peak velocities of a batch run can be lowered using these parameters.
While a shorter batch of only 1,000 m length leads to velocities up to 17 m/s (figure 8), the decrease of the pig friction pressure to 3 bar increases the peak velocities by only 1 m/s (figure 9). The combination of short batch and low pig friction (figure 10) results in an addition of both these effects and in maximum velocities of 18 m/s as well as in a significant decrease of the distance covered at acceptably low velocities compared to the case with short batch and high pressure (figure 8).

Even using wildly optimistic assumptions batch runs are thus not viable and the feasibility of half-batch runs had to be investigated.
3 Half-Batch Simulation

The first thing to consider with respect to a half-batch simulation of the pipeline in question was that no water is available at the locations B and C. It was therefore decided to use the following pigging procedure:

1. The US pig travels from A to B propelled by the pumps at A using water from a river. Air is appropriately vented at B.
2. At B, the water between the pigs is directed into containers. After all pigs have been salvaged, the data recorded by the US pig is reviewed and the pig is prepared for the next run.
3. The batch is prepared using the water in the containers at B. The pigs then travel to C propelled by pumps at B. The water in the containers at B is continuously replenished by the pumps at A pumping water from A to B. Venting takes place at C.
4. For the case studied here, the data review after arriving at C showed that the data set was complete. This had already been confirmed earlier for section A-B. If this had not been the case, the US pig could have been employed again during the following dewatering of the pipeline.
5. Using air compressors at C, the section B-C is then dewatered into containers at B using a batch of disk pigs. The containers are continuously emptied into section A-B by the pumps at B. At A, the water is cleaned and then directed into a river.
6. After the arrival of the batch at B, the pumps at B are replaced by air compressors to facilitate the dewatering of section A-B.
7. Section A-B is dewatered and the pigs are recovered at A.

There are two safety criteria to be considered during a half-batch run:

1. The pressure at the highest point already filled with water must not drop below the saturation pressure of water at the given temperature. In this case the batch might rupture and the parts might later collide, causing a water hammer possibly damaging the pipeline.
2. The maximum admissible pressure for the given pipeline must not be exceeded. The air density in the gas-filled part of the pipeline can be considered constant over the whole length for a given pressure and the given height profile. Consequently, it is the pressure at the lowest point of the part already filled with water that must be monitored to ensure compliance with this criterion.

To ensure safe operation according to these criteria, it is sufficient to vary the air pressure depending on the position of the batch front. This pressure can be adjusted using the following methods:

1. **Compression by pump**: the pressure can be increased by keeping the end of the pipe closed while the water pumps are running. This option is available only while filling the pipeline. The spatial rate of pressure increase thus achievable is limited, but increases as the air-filled volume decreases. It can be enhanced by injecting air into the gas column in front of the batch. In the case discussed here this was not necessary. Under certain circumstances the delivery pressure of the pumps may become a limiting factor.
2. **Venting**: This enables a constant or falling air pressure and even an increase smaller than through compression, all while the pig is travelling. Used during dewatering, it facilitates sharp pressure decreases. This was not necessary for the case discussed here, however.

3. **Expansion**: This option is only available during dewatering, with the pressure dropping at a specified rate while the amount of air in the pipeline is kept constant.

4. **Use of compressors**: These can be used to achieve constant or rising pressure as the pipeline is dewatered.

The main result of the simulations was a corridor for the admissible air pressure depending on the batch position as shown in figures 11 and 12. There the lower red line is the boundary associated with the risk of a water hammer, while the upper red line stands for reaching the maximum allowable pipeline pressure. For the calculation of these functions conservative assumptions were made concerning e.g. friction and the saturation pressure, which resulted in appropriate safety margins.

Figure 11: admissible air pressure corridor for the filling of section A-B from A to B (red) and proposed air pressure (green)
Starting at A, the pressure is increased through compression on the first 67 km, after which venting commences to keep the pressure constant. The slight pressure dip between km 78 and 88 was included to lower the pressure to be delivered by the pumps (figure 11) while the batch crosses the highest hills of the whole section.

The proposed pressure function for section B-C is somewhat more complicated due to the given height profile. Starting from a relatively high air pressure achieved with compressors before pigging, it involves an initial phase of compression followed by venting at various flow rates and pig velocities until compression again takes place from km 82 on. After the pigs have crossed the lowest valley, a sharp pressure drop is required in order not to cross the upper red line, i.e. exceed the maximum allowable pressure at the valley bottom.

Figures 13 and 14 show the pressures at the location of the pumps during the filling of the both sections.
The corridor and proposed pressure profile for the dewatering of the two sections are shown in figures 15 and 16.
In these figures the corridor has been shifted to higher pressures compared to the filling operation to account for the opposite direction of the friction forces. In addition, the shape of the proposed pressure function (green) is different from the one for filling due to the different processes involved (expansion of a fixed air inventory instead of compression, compression through compressors instead of pumps).
4 Half-Batch Operation

First a conventional pig run in natural gas was carried out to clean the pipeline and ensure it was negotiable for the US pig. Then the pipeline pressure was decreased from 45 to 6 bar at up to 35,000 Nm\(^3\)/h using Open Grid Europe’s mobile compressor unit (figure 17). The remaining natural gas was driven out using air as well as a batch of nitrogen to separate the two gases. Mobile air compressors were then used to increase the pressure to the initial values given in figures 11 and 12.

Figure 17: mobile compressor unit for depressurisation

4.1 Filling the Pipeline

Unfortunately water was not available in large amounts directly at A, but at location D only 9 km further. A few weeks before the first pig run, an artificial pool (figure 18) was therefore built at A with a capacity of 8,000 m\(^3\) and filled from wells at a mass flow rate substantially lower than during the later pigging. This water was then used to transport the batch to D. The pool had to be continuously guarded by a certified lifeguard until it could be dismantled again.

A total of four mobile water pumps (figure 19) was used for the operation, each capable of delivering more than 300 m\(^3\)/h. Two pumps reached this value at outlet pressures of 60 bar. These were were installed at D (see figure 13), while the other two were used first at A and later at B.
During the filling of the sections A-B and B-C a mobile mass flow control unit consisting of several containers (figure 20) was installed at B and C, respectively, combined with a silencer. This enabled the decrease or keeping constant of the air pressure whenever called for (see figures 11 and 12).
4.2 Dewatering the Pipeline

While dewatering the pipelines, the water had to be cleaned of hydrocarbon traces from the pipeline and disposed of at D. For this several silos of activated carbon were used (figure 21). Since activated carbon is alcalic after activation, it had to be acid-treated prior to deployment for the cleaned water to meet the permitted pH value.

Figure 21: water treatment plant at D using activated carbon

Figure 22 shows the mobile compressors used at C and B to dewater the sections B-C and A-B, respectively. Since these screw-type compressors had a maximum outlet pressure of about 26 bar, they could not deliver the pressures of up to 50 bar required to dewater section B-C. This was instead done by evaporation of liquid nitrogen at C (figure 23). Since this was more expensive than air compression, the nitrogen had to be delivered just-in-time to make sure the steep pressure gradient planned between km 98 to km 95 (green line in figure 15, to be read from right to left) could be met and thus ensured that the amount of nitrogen be minimised. This was because with the steep gradient the compressors could be used from the start at 111 km right to 98 km. For the same reason, the pig velocity was reduced between km 98 and km 95 with the evaporator running at full capacity. A steep gradient was also chosen for the proposed pressure profile in figure 15 between 54 and 49 km.
Section A-B could be dewatered starting from B using only the air compressors (figure 16) since no pressures above 26 bar were required. Since the water had to be treated at D rather than A, the half-batch was stopped shortly before arriving at D. Then another half-batch was driven from A to D using air compressors at A to dewater the last part of the pipeline. The resulting pig train was then propelled to A using the air compressors at B.

4.3 Monitoring

The most important prerequisite for safe operation is the constant and precise knowledge of the current position of the batch front, i.e. the interface between water and air. Three methods were used to track the half-batch:

1. The amount of water pumped into or taken from the pipeline was continuously monitored. The precision of this approach is limited by the knowledge of the effective volume of the piping (including branches etc.). The lower parts of the
pipeline may also temporarily be exposed to elevated internal pressures resulting in larger inner diameters. For a 100 km-long pipeline this effect alone can result in errors of more than 100 m.

2. Pressure measurements on each pipeline section, along with the air pressure, were used to infer the current height of the batch front, which could be translated into its position using the height profile. The precision of this approach is limited by e.g. the precision of the pressure measurements and the accuracy of the height profile.

3. The most reliable method of tracking was the detection of pig passages in the field using individual signals. This was done every 1-2 km by field staff working in three shifts.

The whole operation was surveyed from B by a team leader and a simulation engineer, both working in three shifts. The team leader was an experienced operations engineer or senior technician. The simulation engineer was responsible for the continuous monitoring of all safety-related physical parameters such as the batch front position, pressures and mass flows as well as their interpretation. He also acted as a consultant, his tasks including the calculation of various parameters of interest to the team leader for decisionmaking.

Figures 24-27 show the pressure profiles obtained from the actual pig runs.

![Figure 24: planned and actual air pressure during first pig run](image)

During the first run (figure 24), the proposed pressure dip was only partly implemented since the pumps at D (at 9 km) proved capable of delivering the desired mass flow even at pressures above 60 bar.
During the second run (figure 25), the proposed pressure profile was generally adhered to. During the passage of the valley at 94 km the velocity was reduced in order to be able to control the pressure more precisely in this bottleneck. Careful interpretation of the batch front position given at this point by the three methods described above ensured the proposed pressure function (green) could be closely followed.

Figure 25: planned and actual air pressure during second pig run

During the second run (figure 26), the proposed pressure profile was generally adhered to. During the passage of the valley at 94 km the velocity was reduced in order to be able to control the pressure more precisely in this bottleneck. Careful interpretation of the batch front position given at this point by the three methods described above ensured the proposed pressure function (green) could be closely followed.

Figure 26: planned and actual air pressure during third pig run
During the third run (figure 26), the pressure was more or less held constant between km 50 and 30. This was done by continuously evaporating nitrogen at C during that time instead of opting for an expansion phase in between the two intervals of rising pressure as proposed by the simulation. This did not result in a larger amount of nitrogen needed since the pressure would not have dropped below 26 bar before km 30 anyway.

**Figure 27: planned and actual air pressure during fourth pig run**

During the first half of the fourth run (figure 27, km 112-67), the actual pressure was deliberately kept somewhat lower than originally proposed to obtain a higher mass flow from the air compressors. The pressure dip at 32 km was caused by venting. This ensured the pressure between locations D and B was not too different from the pressure between A and D when the pig train was finally moved from D to A after all water had been drained from the pipeline at D.
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With detailed knowledge of the pipeline status obtained and no accidents occurred, Open Grid Europe considers this largest pigging project in the company’s history a full success. The authors would like to thank the following companies whose competence and support have made this possible:

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