THE ROLE OF 'SMART' CLEANING PIGS IN PIPELINE REHABILITATION AND MAINTENANCE

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This paper explores the theory of 'Smart' Cleaning Pigs and explains how they can be used in the rehabilitation and maintenance to ageing pipeline infrastructure. It is based on work pioneered by a pipeline inspection company based in Scotland. The work has focused on the premise that the traditional pipeline pig can be used to *'inspect as it cleans'*. It has resulted in the development of a patented pipeline inspection system, which was deployed for the first time in 1997. 'Smart' Cleaning Pigs are now operated under license in territories as far apart as Nigeria and Australia.

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INTRODUCTION

Hydrocarbon pipelines are a major global asset. Today conservative estimates are that there are between 1.5 and 2 million kilometres of major oil/product trunklines and gas transmission pipelines in production throughout the world [1,2]. The investment in these assets has been substantial and with this investment having been made there is a clear economic imperative to ensure that they are operated for as long as is commercially practical. This means that lines which may have been originally designed for, say a 25 or 30 year life, are actually to be operated way beyond this.

In order to achieve this there are a number of issues which must be addressed. For example, many of these older lines will not have been properly maintained and years of systematic under investment will have resulted in lines which are in a generally poor state of repair. Many will not have been inspected and information regarding their construction and route may at best be sketchy. Some could be choked with debris due to the lack of proper pigging programmes. Others may have been mechanically damaged, or over-stressed due to soil movements and the like. Most will require some form of re-certification and residual life assessment.

This paper explores how 'Smart' Cleaning Pigs can be used in the rehabilitation and maintenance of pipeline infrastructure. It explains the theory behind the technology; discusses some of the experimental and field trials carried out; and outlines the benefits and limitations with this generic technology.

THE 'SMART CLEANING PIG' – THE THEORY

The origin of the 'Smart' Cleaning Pig dates back to the early 1990's. At that time there was a general recognition by many of the oil companies operating in the North Sea, that very little was actually known about the behaviour of conventional pipeline pigs within their hydrocarbon pipeline systems. As a response to this a joint industry research project (the Pigging Technology Project[(1)]), was set up. This work focused, over a 5 year period, on developing a better understanding of the behaviour of cleaning pigs in hydrocarbon pipelines [3,4,5,6,7].

In 1994 RST Projects Ltd (RST) was formed with the aim of developing an affordable pipeline inspection technology which could be used to provide some basic information on the condition and integrity of operational hydrocarbon pipelines. It took some of the basic understanding developed on the behaviour of cleaning pigs and extended this to provide the basis of a pipeline inspection system.

The theory developed went as follows. When a cleaning pig travels along a pipeline it will exhibit certain measurable and quantifiable characteristics. It will travel with its nose at a certain attitude (either slightly upwards or downwards); it will generate a certain amount of vibration as a result of the interaction between its seals and pipe wall; and it will require a certain amount of drive differential pressure across it in order to push it along the line. It will continue to exhibit these characteristics until the environment in which it is travelling changes. When this happens the altered behaviour of the pig will signify the presence of a change.

An example of this is when a pig hits a dent or some other obstruction within a pipeline. When this occurs three things happen. Firstly, the amount of differential pressure (dp) across the pig increases significantly as a result of the pig being forced beyond the obstruction. Secondly, the pig will momentarily slow down and then speed up. Thirdly, the pig will vibrate significantly as it squeezes past the obstruction. If pig dp, vibration and acceleration data can be logged and interpreted then this provides a means of identifying the presence of dents within a pipeline.

[(1)] The Pigging Technology Project (PTP) was a joint industry funded research programme which specifically investigated the behaviour of cleaning pigs. The project was set-up and managed by the oil and gas division of the British Hydromechanic Research Group (BHRG), and was supported by a number of oil companies including; BP, Shell, Total, Amerada Hess and Conoco. Author ① was PTP Programme Manager for 4 years.

The behaviour of a pig passing a dent is illustrated in Figure I.

This lead to the suggestion that if this idea could be extended to cover other features which are present within a pipeline (such as debris, change in pipeline profile and internal surface anomalies), then it may prove possible to develop a basic pipeline inspection capability. Furthermore, should this prove possible then it was recognised that this inspection capability could be offered using a standard cleaning pig with a data recording package added to it. This offered many potential benefits.

It was this theory which has evolved into the 'Smart' Cleaning Pig, a technology which has been patented by RST. Figure II shows the arrangement of a typical 'Smart' Cleaning Pig. It comprises an instrumentation and data acquisition package which is fitted within the body cavity of a standard cleaning pig. This logs information on the passage of the pig whilst in service. This data is then offloaded and analysed.

Details of the background to the project and the development programme are given in [8,11].

EXPERIMENTAL TESTING

In the period since 1995 extensive testing has been carried out using various types of 'Smart' Cleaning Pig. This work continues today. During this time four different experimental test facilities have been used. Details of the test facilities used are summarised in Table I.

Many hundreds of laps of test data have been acquired using different types and sizes of pigs. During these experiments various instruments have been deployed on-board the test pigs in a variety of combinations. In each case the data logged was stored using a custom-built data acquisition package. The data acquired was then analysed using in-house developed software. Matlab has been used as the development tool. Details of some of the more technically challenging aspects of this work have been presented in [8,9]. For the purposes of this paper some of the main findings are summarised as follows:

Performance:
It was found that the dynamic behaviour of a cleaning pig was consistent and repeatable through test sections. For example, those sections of pipe which induced higher vibration effects, did so repeatedly. It was found that these behaviours did change as the polyurethane seals and guide disks became worn. However, this was found to happen in all test sections. As a result it meant that those which induced higher vibration still did so relative to adjacent pipe spools, even with worn disks. The measurable behaviour of the pig did vary with line diameter. However, it did so only in terms of absolute values and that the relative nature of the measured behaviours were again observable across different line sizes.

Size:
It was found that the required instrumentation, electronics and batteries could be sufficiently miniaturised in order to fit within pigs which could be deployed in lines as small as 6" diameter. The larger the diameter of the line then the more range which could be achieved.

Functionality:
It was found that the data acquired from the on-board instrumentation varied significantly and consistently for known changes in the condition of the test facilities. Sections which either had a known change in bore, a change in surface roughness or the presence of debris or other foreign matter, could all be readily detected.

Instrumentation:
Various types of instruments were tested in order to establish their usefulness. The main findings are as follows:

Absolute Pressure: The acquisition of accurate line pressure data was achieved. The main issue which had to be overcome was the error associated with the temperature compensation of the instrument. This was particularly significant given that the pressure cell was expected to accurately measure line pressures from 0 - 200 barg over a temperature range of 0 - 70°C. This was achieved within acceptable error limits. However, the usefulness of measuring of absolute pressure to identify features within a pipeline was not considered to be significant. Specifically, it was only found to have relevance to features which would cause overall changes in hydraulic gradient, such as a change in the internal surface roughness of the pipeline. Local features, such the presence of wax, were not found to cause a measurable change in absolute pressure.

Differential Pressure: The acquisition of pig differential pressure (dp) data was achieved. [3,5] had suggested the importance of pig dp as the governing factor which controls the performance of a cleaning pig. This had been explored in some detail with regard to debris transportation. However, it had not been studied in connection with its ability to detect changes in pipeline condition. Measurements of dp of the order of 5 – 10 millibar were achieved. This has been possible by the use of a true differential cell. This device is in effect a diaphragm with pressure from the rear and the front of the pig being applied to either side of the diaphragm. The deflection of this diaphragm gives a direct measure of the dp across the pig. This devise was found to be very sensitive and capable of detecting both subtle and gross features present within the test facilities.

Temperature: The acquisition of fluid temperature data was achieved. It was found that mounting the temperature sensor internally within the instrumentation pack provided a good measure of line temperature, whilst providing quite considerable engineering benefits in terms of simplifying the design of the data acquisition pack. Although in its own right temperature was not believed to offer any direct measure of pipeline feature, when used in conjunction with other data, it was felt that it would provide confirmation of temperature dependent effects such as the drop out of wax, or the formation of hydrates.

Acoustics: Investigations were carried out into active and passive acoustics. In the case of active acoustics, transponders were placed on board a pig within a test pipeline. The test sections were then either left as bare metal, or coated with synthetic wax. A signal was generated and its response from the pipe measured. Clear differences where observed between coated and uncoated pipe, as shown in Figure III. Coatings as small as 1 mm were tested. However, it was found that when the carrier pig was in motion, these effects could not be filtered out from the noise of the pig. This work is still ongoing. Investigations were also carried out in to the use of simple microphones mounted within the pig to measure the noise generated by the pig seals and the pipe. Although, this did generate some useful information, it was found that the microphone tended to act more like switch, in that there was often either a ‘null’ response or a full scale response, with little sensitivity between the two extremes. The use of passive acoustics was discounted.

Vibration: Measuring the vibration of a pig as it travels along a test pipeline was achieved. A pig vibrates as a direct result of the interaction between its seals and internal surface of the pipe. The amount of vibration will depend upon the many factors, such as service (oil/water/gas), pig speed, and surface condition of the pipeline. Also, vibration is an extremely complex parameter to measure, as it is sensitive to the location of the measuring instrument (and how it is physically mounted). Vibration also occurs over a range of frequencies. Furthermore, any vibration will be transmitted from its source (i.e. the interaction between the pig cup and pipe wall) through one or more non-linear springs, in the form of the polyurethane seals and guide disks. However, given all of these issues it was still possible to measure the vibration effects of a pig, by mounting an accelerometer within the body cavity. This instrument measures the vibration response at a specified location. This signal is then filtered across 5 frequency bands ranging from 158hz to 3kHz. Repeated testing of this instrumentation has shown its ability to consistently detect subtle changes in the internal surface condition of a test pipeline.

Acceleration: The ability to measure the rate of change of the velocity of the pig has been achieved. In this case an accelerometer has been specially mounted on shock mounts within the body of the data acquisition unit. This has particular relevance to gas pipelines where the pig will stop and move off rapidly (velocity excursions). A secondary benefit to result from the use of an accelerometer was the ability to measure the angle of tilt of the pig. This angle of tilt can be combined with the pig velocity, to give the local shape of the pipeline. Figure IV shows the calculated shape of a known test section.

Although the various instruments did indeed provide useful information it was their use in combination that proved most informative. Russell, Smith et al [8,9] discuss how standard, commercially available instrumentation could be mounted in combination on a pig and how the data acquired from this spread of instruments could be analysed to provide information on the condition of a pipeline. It was found that the careful selection of instrumentation could provide information on:

1. The presence of certain components within a pipeline – bends, valves, tees and wyes.
2. The presence of mechanical damage (dents) and other changes of internal bore.
3. The presence of changes in the general surface condition of the pipeline associated with debris, synthetic waxes and even some forms of corrosion.
4. The vertical profile of the pipeline over localised sections of a pipeline.

The ability to detect these features was found to depend upon the correct selection of instrumentation. This has lead to the standardisation of the spread of instruments to be deployed. This spread comprises:

- True differential pressure cell
- Vibration sensor
- Accelerometer
- Temperature sensor

It was this spread of instruments which were engineered into the first prototype 'Smart' Cleaning Pig.

RESULTS - FIELD STUDIES

In the summer of 1997 the first field trials using a 'Smart' Cleaning Pig were carried out in the UK Sector of the North Sea. To date, 'Smart' Cleaning Pigs have been used to survey about 2,500kms of pipeline. As a result of this work it has been possible to investigate the theories which had previously been developed in the lab, and prove their validity in the field. Some of the key findings are discussed below. In each case the findings are illustrated using field data.

Weld Detection: The use of the vibration sensor to detect individual girth welds has exceeded expectations. In the case of oil pipelines this effect is very clear. The signature is even more pronounced the faster the pig is travelling. Figure V shows a typical vibration trace at 0.5m/s and a trace at 2.5m/s. The difference in the amplitudes of the responses is self-evident. Also, it was found to be necessary to set the data sample rate around 13Hz, to ensure that all welds are detected. In the case of one 170km oil pipeline which has been surveyed on three separate occasions exactly 13,950 welds have been found between the pipeline end flanges, which gives a 100% tie-in with the known weld count in the pipeline. Where this sample rate is too low the welds can appear randomly through the data trace as shown in Figure VI. These responses can appear to move in subsequent surveys and can be miss-interpreted as features.

Component Detection: The ability to detect confidently welds means that is possible to breakdown a pipeline into individual parts. This is easily applied to individual pipe spools which can subsequently be tagged. It can also be applied to other component parts and when the vibration and dp data are combined it allows for signatures of these individual parts to be developed. Figure VII shows the signature for an Inconel clad subsea tee piece. In this case the tee has been fabricated from 6m pipe spools, the regular pattern of which shows up clearly against the 12.2m sections either side. What is also evident is a vibration kick at the branch of the tee itself and a significant decrease in pig dp due to the internal cladding of the tee.

Debris Detection: The experimental testing suggested that pig behaviour would change significantly when it passed through locations of debris. This has indeed been found to be the case. This is best illustrated in waxy crude pipelines. In these lines distinct zones of abnormal pig behaviour have been observed. The behaviour consists of the pig pitching violently, which is combined with a significant vibration effect. These zones have been seen to last for a number of kilometres, before the behaviour of the pig reverts back to a ‘normal’ condition. What has been found is that these zones have a temperature dependency and that as the temperature profile in the line changes, so does the location of these zones. What is more the onset of these behaviours has been very closely tied in with the known wax formation temperatures of the crude. It is therefore believed that these behaviours relate to the wax drop-out zone within a pipeline. Figure VIII illustrates the difference in pig vibration between a clean pipe and waxy section.

Mechanical Damage Detection: Pig behaviour has been found to give a reliable and consistent measure of the locations of mechanical damage within a pipeline. The presence of dents in particular has proven readily detectable. The unique combination of an increase in pig dp, a slight local change in pig velocity and an increase in vibration, have proven to be quite detectable. Changes in internal bore of as little as 0.4% have been located. Figure IX shows a bidi pig passing a region of mechanical damage with a reduced bore. Table II shows some typical reductions in bore and their corresponding increase in pig differential pressure. This table refers to bidi type pigs in relatively clean oil pipelines.

Vertical Profiling: It has been possible to develop local vertical profiles of pipelines, which have been linked together to give a composite strip map. This has been possible by combining the inclination data from the on-board accelerometer with the calculated local pig velocity profile. A numerical integration method has then been used to give the shape. An example of this is given in Figures X and XI. In this case Figure X is the raw data and Figure XI the resulting profile of the pipeline. The use of this technique is discussed in [10].

The consistency achieved with this technique has been surprising good. In the case of one particular pipeline which is known to be stable and which has been surveyed on five separate occasions, its has been possible to compare the profiles generated. Table III details the error bands and the percentage of local profiles falling within these bands. For comparison a typical accuracy for a Mapping Pig [12] has been included. This suggests that the results from the ‘Smart’ Cleaning Pig are of a similar order to a Mapping Pig.

A comparison has also been made between vertical profile data acquired from a 'Smart' Cleaning Pig and other data from an ROV survey. An example of this comparison is shown in Fig XII. What is of interest here is the relatively close tie in between the two survey methods. Where there are divergences between the methods, such as at the minimum point between KP4.75 and KP4.8, the error has been tracked down to limitations in the ROV data rather than with the pig data.

Condition Assessment: The ‘Smart’ Cleaning Pig has the ability to carry out a simple first pass condition assessment of a pipeline. This technique has been developed in-house from observations made on the way a pig passes through straight pipe sections. It had been observed that lines which have been well maintained, the pig behaviour between welds is relatively smooth, as has been illustrated Figure XIII. However, in older lines which may not have been as well maintained, the behaviour has been found to be much ‘noisier’.

It has been possible to calculate the size of the vibration response in each pipe spool. This has been done by calculating the area under the response curve. This process is then repeated for every single pipe spool in the pipeline. A comparison is then made between the response for each spool and a rolling average of nearby spools. The results are then plotted in the form of a ‘Condition Histogram’. The overall shape of this histogram gives an indication of the overall condition of the pipeline. Figure XIV illustrates this.

In this case the response of the pig has generated a relative ‘tight’ histogram, with most of the responses clustered close to the mean. However in the case of an older pipeline with more noise, the shape of the histogram would be flatter. Field trials suggest that a pipeline in relatively 'good' condition should have fewer than 6% of the pipe spools producing a response greater than +2 standard deviations from the mean. In the case of pipelines in generally poorer conditions this has been found to increase to 9% or more of the pipe spools.

APPLICATION TO PIPELINE MAINTENANCE AND REHABILITATION

The ability to carry out a basic inspection of a pipeline using a cleaning pig offers many potential benefits. The fact that the data acquisition tool can be deployed on-board a cleaning pig means that the much of the risk of inspecting a pipeline can be avoided. The equipment can be deployed on-board a pig which is being routinely pigged through the pipeline. Where no such pigging operations are being carried out it can be deployed on-board pigs which will have the greatest likelihood of successfully passing through the pipeline.

With the development of ‘Smart’ Cleaning Pig pipeline operators can begin to consider the prospect of routine monitoring of a pipeline in a practical and relatively straightforward way without the expense of deploying a full Intelligent Pig. This means that many are beginning to look to specify the routine use of ‘Smart’ Cleaning Pigs as part of their operational maintenance programmes.

Another important use of this type of technology is as part of rehabilitation programmes. In such cases the deployment of ‘Smart’ Cleaning Pig can be treated as a precursor to other technologies. The ability to deploy the data acquisition unit on-board a cleaning pig means that basic information on the make-up, mechanical integrity and general condition can be developed as part of the decision making process. It can also provide information on the severity of the condition of the pipeline and the location of the main areas of concern.

Although there are many obvious benefits with this technology, there are certain limitations. Upper most amongst these is the fact that this technology cannot currently confidently detect the presence of corrosion on the pipe wall. A further limitation is that the technology cannot determine the precise size of mechanical damage and its relative radial (o'clock) position.

CONCLUSIONS AND FURTHER WORK

A new and radically different method for inspecting hydrocarbon pipelines has been developed. The 'Smart' Cleaning Pig technology which has been developed in the lab over the past 6 years, has been successfully transferred into the field.

The use of 'Smart' Cleaning Pigs has been shown to provide valuable pipeline management information. Specifically the ability to detect and locate mechanical damage; provide an assessment of the overall pipeline condition and confirm the local vertical profile has been shown to be a feasible part of a pipeline maintenance and rehabilitation programme.

The 'Smart' Cleaning Pig technology has been shown to function in both liquid and gas pipelines. It has proven itself to be a low risk and highly reliable inspection technology. It is now being specified as part of pipeline maintenance and rehabilitation programmes which are being implemented by a range of oil companies both the North Sea and beyond.

Further development work is underway. This will see the technology move towards providing some form of corrosion detection capability. It will also see the upper temperature range move towards the limit of that which can be support by cleaning pigs with polyurethane parts.

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TABLES

Test Rig	Location	Length	Diameter	Materials	Configuration
RST	Edinburgh	44m	10”	Steel	Indoor never ending loop for continuous pigging
Heriot-Watt University	Edinburgh	25m	6”	Steel	Single shot rig, fully instrumented
CALtec	Aberdeen	250m	10”	Steel plus visual	Never ending loop with visual section and dip
McAlpines	Ellsmere Port	170m	12”	Steel plus visual	Single shot facility

Table I - Test Facilities Used

Diameter Changes	Differential Pressure (bar)
Clean Linepipe	0.1 - 0.4
0.4% ID Reduction	+0.15
0.8% ID Reduction	+0.2
1.2% ID Reduction	+0.3

Table II - dp Response to Small Bore Changes

Method	Vertical Error Band*	% of Test Cases
'Smart' Cleaning Pig	+/- 0.09%	100%
'Smart' Cleaning Pig	+/- 0.05%	80%
Mapping Pig	+/- 0.05%	n/a

* Quoted as a percentage of the horizontal distance travelled by the pig

Table III - Vertical Accuracy

FIGURES

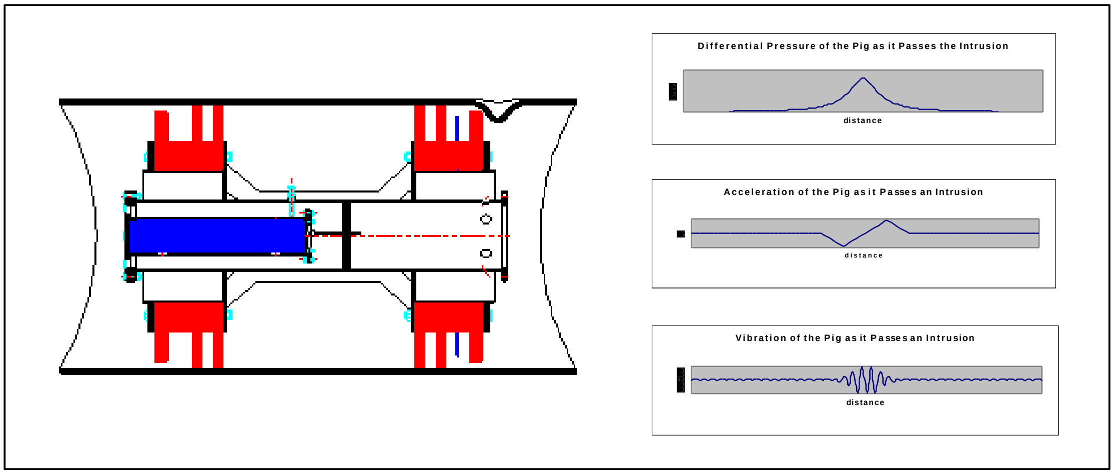


Figure I – A pig passing a dent

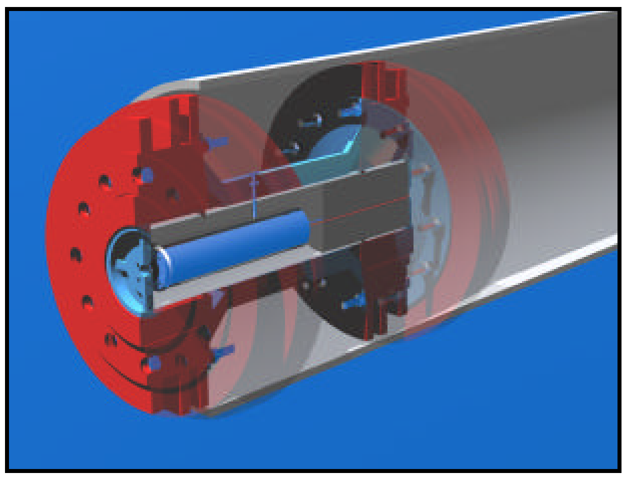


Figure II – A typical ‘Smart’ Cleaning Pig

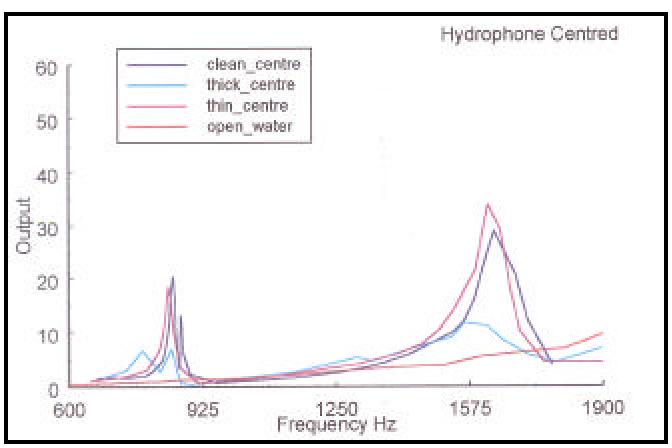


Figure III - Acoustic effects

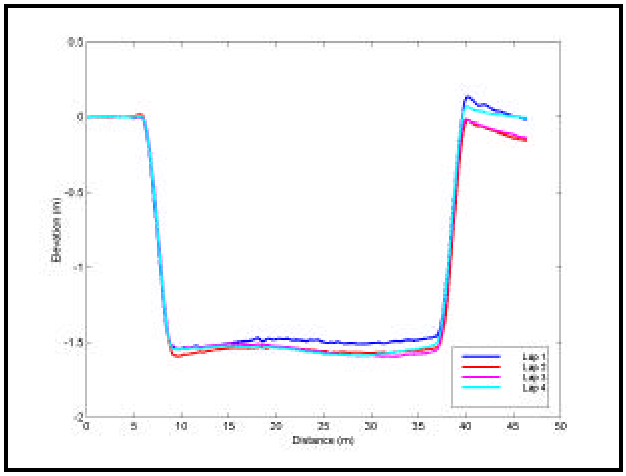
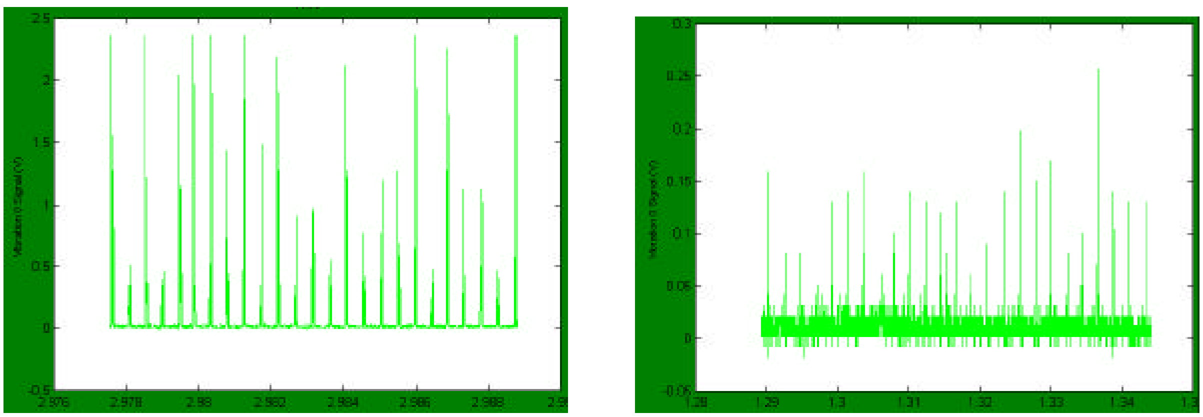


Figure IV - Local Shape of a pipeline



Vibration trace at 2.5m/s

Vibration trace at 0.5m/s

Figure V – Weld profile

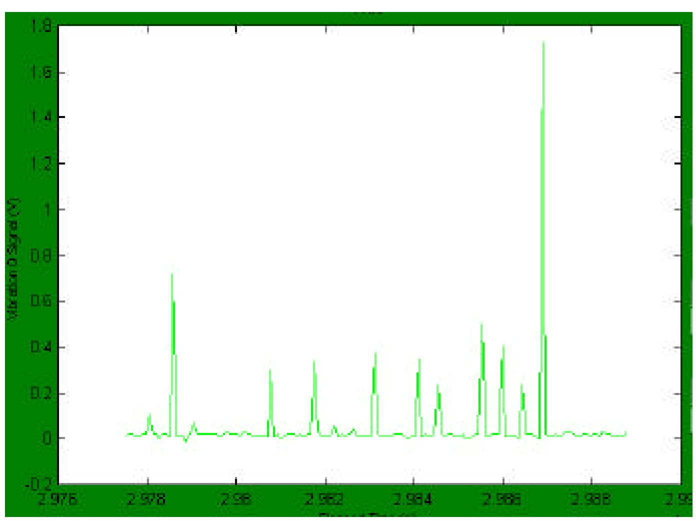


Figure VI – Welds resampled

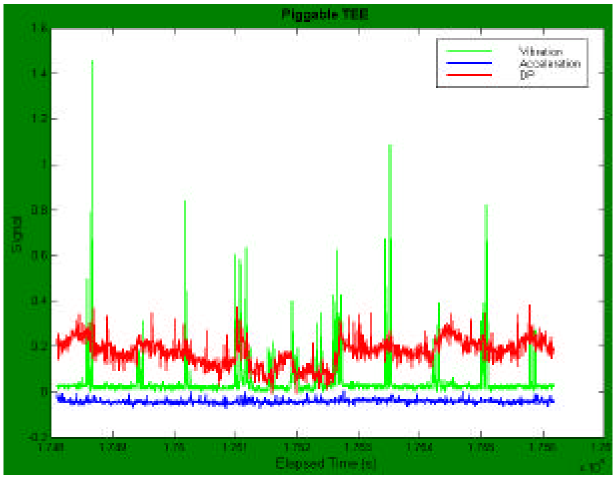


Figure VII – Signature for a tee piece

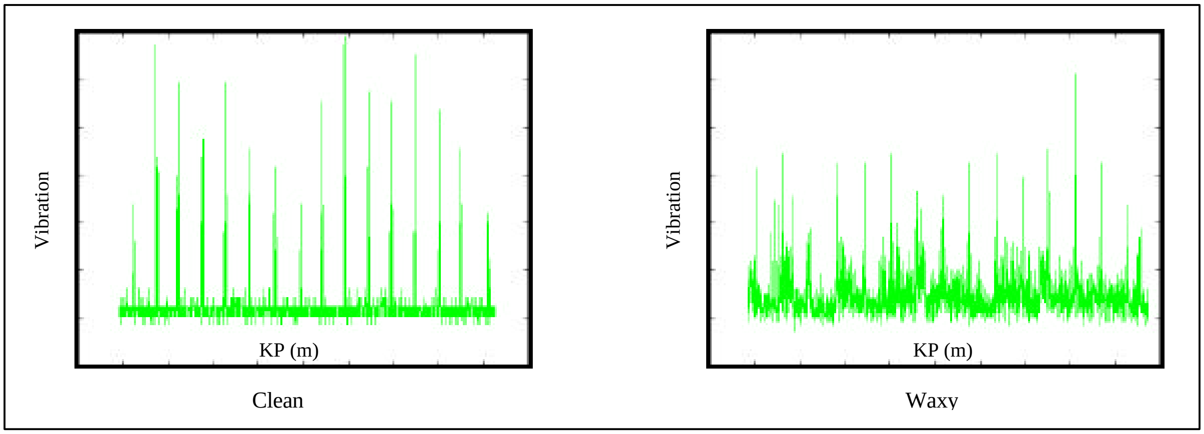


Figure VIII – Pig vibration in clean and waxy pipeline

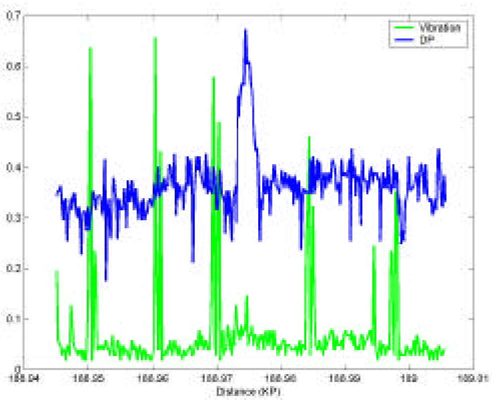


Figure IX – A pig passing a dent

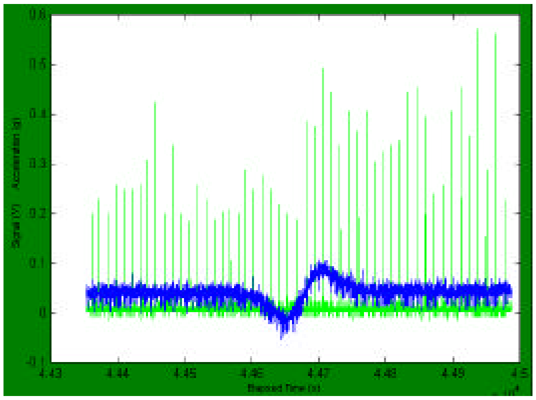


Figure X – Raw accelerometer data

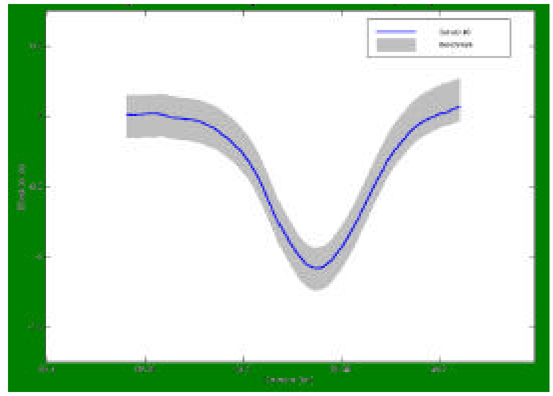


Figure XI – Pipeline profile

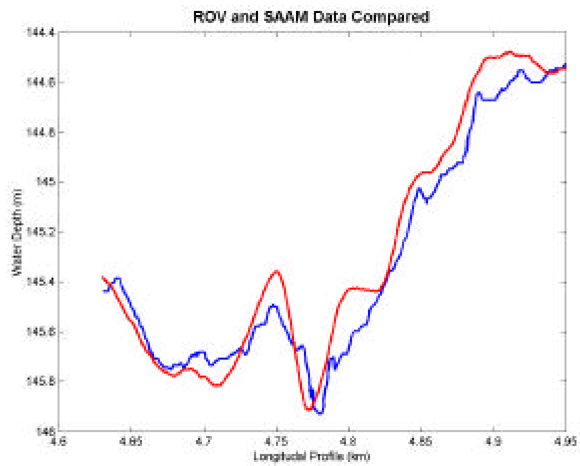


Figure XII – ROV and SAAM™ data compared

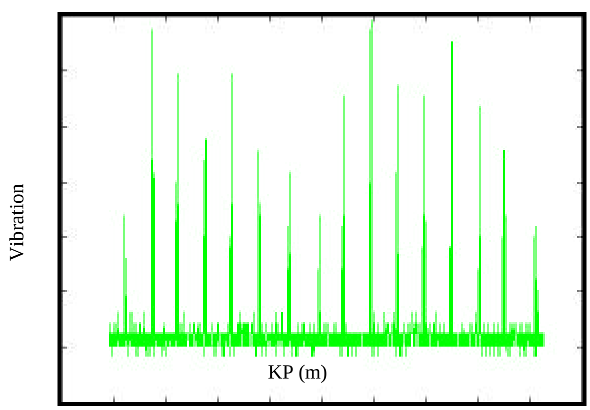


Figure XIII – Weld profile in a clean pipeline

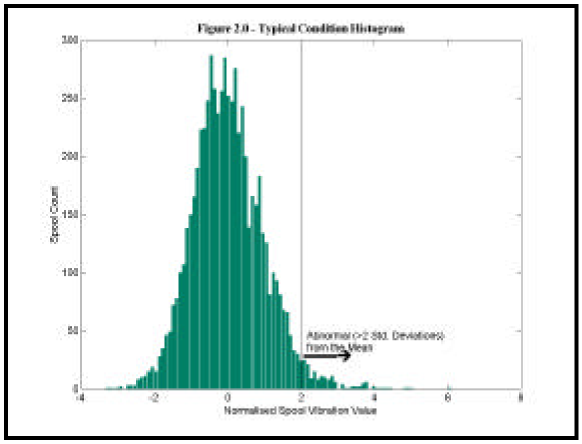


Figure XIV – Condition Histogram