

TRACTOR PIG

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Abstract. *In order to maintain the integrity of its pipelines, PETROBRAS S.A. carries out constant inspections using non destructive testing technologies. Usually, internal inspections are carried out by self-contained intelligent pigs, which, driven by fluid flow, measure pipeline features of interest, that can be, among others, quantification and qualification of pipe wall metal loss due to corrosion, stress corrosion cracks, fatigue cracks, dents and crushing. However, due to their project conception, some pipelines cannot be inspected by conventional pigs. This is the case for some risers, which are the connections between the top side of an off-shore platform and a pipeline on the seabed. For these, the access is difficult, nearly always from one end only and there is no pig receiver.*

This paper deals with the development of a crawler pig especially constructed for these non-piggable lines. Self-powered by a central electric motor, fed and controlled by an umbilical cable, this tool is capable of advancing, reversing and stopping at desired points, even in vertical regions, according to the operator's needs, who will be visualizing the inspection data in real time and identifying places where a new scanning is necessary. Equipped with three caterpillar tracks, symmetrically placed and each one mounted on an expansion mechanism, the pig obtains maximum traction possible by fitting to the pipe diameter, which makes it a multi-size tool. As a result of extensive and applied engineering, the tractor pig was developed to operate in hazardous environments and under high pressure, a fundamental aspect for a tool which will work inside ultra-deepwater pipelines. It is a state of the art concept and is one of CENPES answers to the challenge of inspecting risers and non-piggable pipelines.

Keywords. *pig, self-powered, tractor, inspection, pipeline, riser*

1. Introduction

Petrobras has been improving its non-destructive inspection technologies in order to achieve excellence in pipeline integrity. Much research and development has been engendered. New methods and techniques emerged to meet the challenges. Nowadays one of the biggest challenges in pipeline inspection is related to those pipelines where the access is difficult or even impossible by conventional methods, such as deepwater flow-lines specially the steel catenary riser pipes.

Risers are the pipes used to transport product from a point on the seabed to the platform or vice versa. Usually they are connected to an undersea manifold, well-head, or another flow-line. The point where it touches the seabed is called the Touch Down Point or TDP. Because of the floatation movement of the pontoon and the submarine streams, the TDP becomes a critical region subjected to crack-like defects due to fatigue. So, a thorough inspection must be made in order to prevent catastrophic failures which cause material loss and damage to the underwater environment, due to product leakage. Inspection with conventional smart pigs is not a feasible alternative since the riser's operation scheme and structure design do not permit it. Another kind of approach is necessary, with innovative and specific solutions for this problem.

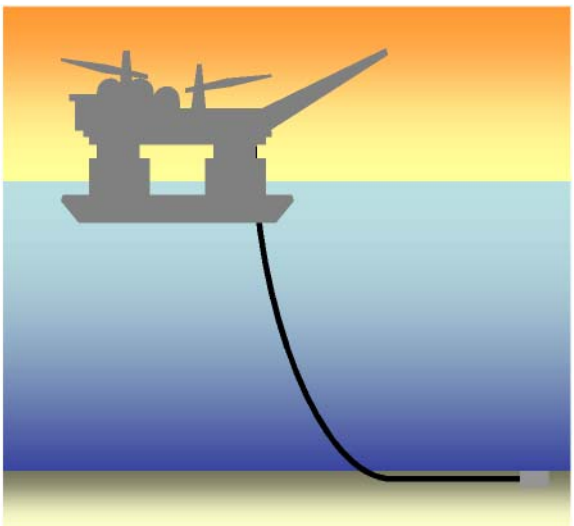

Figure 1. Steel catenary riser in free hanging layout.

One of these solutions was the development of a tool equipped with an adaptable inspection module capable of utilizing different non-destructive testing methods, according to the needs. Examples of these methods are, among others, automated ultra-sonic and/or ToFD (Time of Flight Diffraction), MFL (Magnetic Flux Leakage) and eddy currents. To carry this inspection system in the riser's horizontal section and in the TDP bend, the construction of a tailor-made tractor pig, similar to a train engine and wagons, was necessary for this application.

As part of this idea, it was proposed that this tractor would have the ability of moving and stopping in vertical sections, supporting it's own weight and that of the inspection module and advance and reverse according to the inspector's wish. This would alleviate the umbilical cable load. Another important feature is the ability of adapting to different diameters, so, it had to be a multi-size tool, because the riser has diameter variations along its length. Furthermore, this allows the tractor to be used in a large range of pipelines.

The prototype was designed based on these parameters and taking into account the conditions inside the pipeline at water depths of two thousand meters.

2. Boundary conditions

To build the prototype some boundary conditions were established. The first one is related to the kind of hazardous environments that it will operate in and the huge pressure to which it will be submitted. To satisfy these conditions, the motor system must be sealed inside a vessel filled with a specific oil and have a system to equalize the pressure. To seal an electric motor, the use a brushless type is recommended, because the oil used to compensate the pressure causes electro erosion in the brushes which releases a dust, thus damaging the motor. This motor will be fed by means of an umbilical cable.

The second condition concerns the kind of work it will execute. The first method selected for inspection was ultra-sonic inspection with pulsed waves, and it demands a constant scanning velocity of about 0.1m/s. For available commercial motors the rotational speed has to be reduced and the torque needs to be increased. So, it is necessary to use a reduction box such as, for example, a planetary one. The planetary reduction box is a good choice for two basic reasons: it is compact and it has a high reduction rate.

The third and final condition is the diameter variation, or multi-size ability. Sometimes inside the riser there are some variations in internal diameter from one section to another, so the pig must have a mechanism capable of doing this adaptation automatically.

These conditions described above were the first steps in the conception of the prototype. They defined that it would be constructed with an electrical motor, VAC brushless, sealed inside an auto-compensated vessel filled with oil and this motor would be coupled with a planetary reduction gearbox. The pig would have an expansion-retraction mechanism, making it able to adapt to any diameter inside the riser pipe.

3. Theoretical development

The project of a tractor pig can have various options. Wheels or tracks can be used, one motor in a single vessel, two or more in different vessels, it can be similar to a small car or have radial symmetry with three or more axles. It can be totally controlled by electronics or have a mechanical adjustable speed controller. Any option is good, but, for each type there are some advantages and disadvantages. To define the best way to construct it, some calculations were necessary.

At the start of the project a diameter variation range from eight inches to fourteen inches was established. A load capacity that would not exceed 120 kilograms force was also defined.

The load capacity is the amount of load that the tractor can pull moving upwards inside a vertical section considering its own weight and the weight of the rest of the system. It is related to the traction force in the wheels or tracks and thus to the torque in these. The traction is also dependent on the force applied to the wheels against the pipeline wall which will be responsible for the friction force. If the torque is too high for the pressure of contact, the result is slippage and no movement. If the torque is too low, the tractor will not be able to move the load. So, the torque has to be sufficient to set the system in motion and the contact pressure as high as possible to avoid slippage occurring.

3.1 Contact force

To stop vertically inside the riser, a force against the internal wall is necessary. This force is applied by the expansion-retraction mechanism which consists of three pairs of pantographs distributed in a radial array spaced at 120º. The pantograph's opening is made by the action of a traction spring. The problem with this system is that it is very efficient for large diameters and inefficient for small ones. The schematic figure shows a single pantograph where $\mathbf{F}_s$ is the force exerted by the traction spring, $\mathbf{F}_c$ is the contact force applied against the wall and q is the angle between the arm and the perpendicular direction with the F_s force:

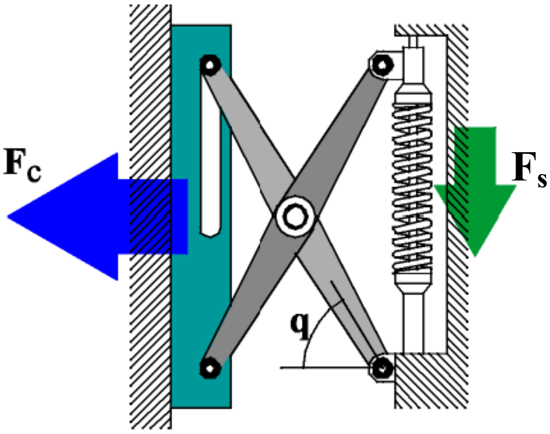

Figure 2. Schematic pantograph model

The equation that demonstrates the relation between the forces Fs and Fc is:

$$\mathbf{F}_s = \mathbf{F}_c \cdot \mathrm{tg}\ q \quad (1)$$

$$\mathbf{F}_c = \mathbf{W} / \mu \quad (2)$$

W is the weight of the tractor and the inspection modulus and μ is the static friction coefficient. To stop vertically, the contact force must satisfy the condition given in equation (2).

The equation above shows that as q grows, the action of the force exerted by the spring decreases. Thus, it becomes clear that for small diameters larger springs would be necessary. To solve the problem, when the tractor is running inside pipes with small diameters, a second pair of conical compression springs acts to increase the pressure. Another solution is to use a different mechanism, more complex, capable of applying a constant contact force in any diameter.

Considering the diameter variation range and the entire system weight, the spring was dimensioned to exert a force sufficient to maintain the tractor vertically when stationary.

3.2 Necessary torque

To set the entire system in motion, an initial torque is necessary. This takes into account the inertia of the system at rest. In general, the motor itself has a peak torque which is sufficient to start the movement. To avoid slippage, the traction force must be less than the friction force, thus promoting rolling. However, to put the system in motion it is necessary to accelerate it from the rest position to it's working velocity. The final torque was discovered considering a total weight (W) of 1200N, a sprocket wheel radius (R) equal to 12.7mm, a friction coefficient (μ) equal to 0.2, a track with a contact length of 200mm and that the tractor reaches the working speed of 0.1m/s after 2s. A simplified summary of the motor torque calculation is shown in the table below:

Table 1. Total motor torque calculus summary

Formula	Nomenclature	Symbol	Value	Unit
$d\omega = dv / dR$	Angular speed	ω	7.8740	rad/s
$d\alpha = d\omega / dt$	Angular acceleration	α	3.9370	rad/s^2
$I_m = I_{motor} + I_{gearhead}$	Motor inertia	I_m	0.000305	kg.m^2
$I = m \bullet R^2 + I_m$	System inertia	I	0.0196	kg.m^2
$\tau_i = I \bullet \alpha$	Inertial torque	τ_i	0.0772	N.m
$F_c \geq W / \mu$	Contact force	F_c	7200.0000	N
$F_f = \mu \bullet N = \mu \bullet F_c$	Friction force	F_f	1440.0000	N
$F_t = W + \tau_i / R < F_f$	Thrust force	F	1206.0787	N
$\tau_t = F_t \bullet R$	Total torque	τ_t	15.3172	N.m
$\tau_m = \tau_t \bullet$ S.F. S.F. = 3	Motor torque	τ_m	45.9515	N.m
$P_m = \tau_m \bullet n / 7120,76$	Motor power	P_m	361.8135	W

3.3 Speed control - The bend problem

Every pig when traveling inside a pipeline is subjected to different types of forces. Sometimes, the action of these forces makes the pig turn around its own axis of symmetry. This is an inherent problem in the project of tractor pigs. The wheels or tracks will follow different paths inside the pipeline, sometimes they will change their positions, so that a track traveling in the 6 o'clock position at one moment can go to the 12 o'clock position in the next, and so on. In linear segments this is not a problem, but, when the pig reaches a bend, all tracks must change their speeds following a rule according to the radius they are performing. Thus, considering the bend radius, the track that is traveling in the outer radius must have a speed greater than the one that is acting in the inner radius. All the speeds can be discovered knowing the position of a reference track at the exact position related to the central radius of the bend. So, settling a track as the reference and considering the angle between this track and the central radius varying from 0º to 420º, the graph below shows that there is a fazed disparity of 120º between each consecutive track. This graph shows a three track tractor pig moving inside a 10 inch pipeline with a bend radius equal to 5 diameters. Considering that the tractor is turning around its symmetry axis as a screw.

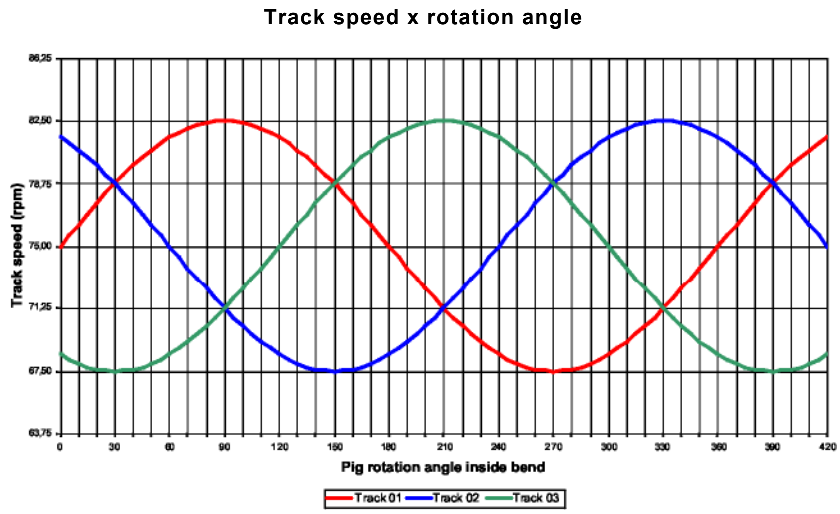

Figure 3. Relation between track speeds and their position inside the pipe.

The difference between the tracks is reflected in torque distribution. The traction torque decreases with speed growth. So, tracks traveling in the inner radius will require less speed and more torque. A constant torque and speed can lead to a situation in which the pig will turn around on itself and become trapped inside the bend. This would happen if the inner tracks do not slip.

Assuming that no slippage will occur and to prevent the tractor becoming trapped inside the pipeline, some speed control solutions were proposed. Different types can be used according to complexity, cost, and dimension requirements. The first suggestion was to develop a tool with one individual motor for each track. Using this configuration, each motor could be controlled separately according to the required speed. To accomplish this task, a P.I.D. (Proportional Integral Derivative) controller with dedicated electronics and integrated with the motors would be necessary, but this would imply the addition of one more vessel to the tractor train. On a bend, the difference in requested torques would be felt as a current variation in each motor. These current values can be computed, compared and result in a control by the P.I.D. To use this system respecting the boundary conditions the use of three small motors with 1/3 of the capacity of a single one would be necessary. However, as the motor gets smaller, it's speed increases, requiring one planetary gear head with more stages to each motor, increasing the weight and size of the entire system. Besides the compactness problem, the umbilical has to be able to supply all the energy necessary to feed the entire new configuration, including: the inspection modulus, the motors and control electronics.

The second solution proposed is to use a self-governing, CVT-type (constant variable transmission) mechanical adjustable speed drive. This mechanism, coupled to each track, can control its own speed according to the torque variation by means of a torque sensitive governor inserted in the output shaft. With this solution, the system can maintain one single motor. The problems with this solution are: load capacity, complex project, and the dimension requirements which call for a small mechanism.

Another mechanical solution of simple construction is a bidirectional slip clutch. As the speed in the inner track is the same as the motor's, higher than it should be, the requested torque becomes lower than necessary, increasing the relationship load / thrust. This works as a brake to the motion, because the track thrust force becomes insufficient to pull the load. Adding a slip clutch, when this brake force grows above a fixed limit, the sliding of the clutch discs compensates for the difference in velocity.

The final solution is a tractor pig similar to a little trolley. This solution is very common all over the world as a horizontal pipeline inspection tool. Nevertheless, their performance in vertical sections are not known. As stated before, risers behave differently from conventional pipelines and their movements can force the trolley to move in a position where the wheel velocity can not be compensated even by a single differential. In this case, a PID controller can be a good solution.

4. The prototype

The first prototype was constructed based on the simplest solution which would attend the boundary conditions set. One single brushless motor was selected and mounted with a planetary gear head. There is a transmission box at the output shaft of the gear head which distributes the torque among the three traction tracks by means of a set of helical gears. The axle that transmits torque to each track system is telescopic, so it can deal with the diameter variation. The expansion mechanism is a simple pantograph that has 4 traction springs for large diameters and two conical springs for small ones. The entire motor assembly is sealed inside an oil compensated vessel. The actual variation range is 10 to 23 inches.

Figure 4. Tractor pig prototype photograph**.**

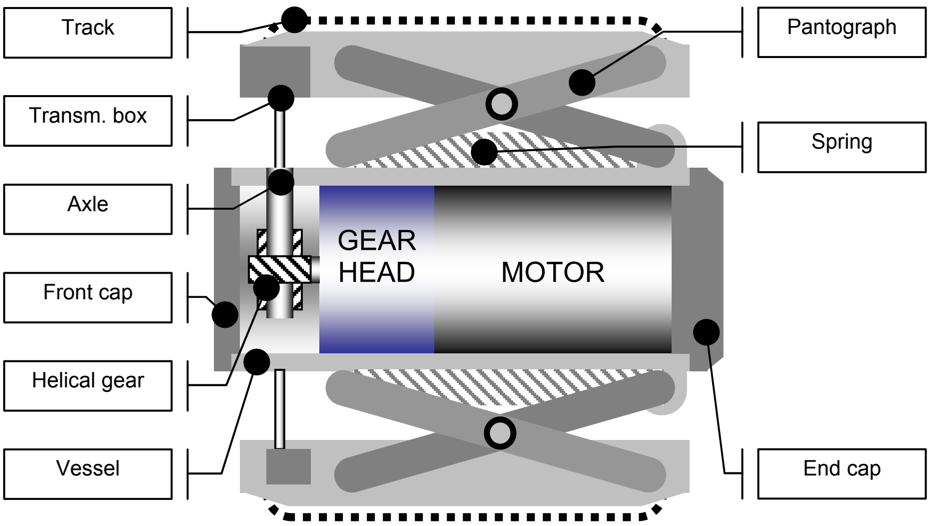

Figure 5. Tractor pig – schematic view

5. Conclusions

The first prototype was completed with some deviations from the original idea. Some adaptations were necessary for the model to function under actual conditions. As an example, the track system was modified and the contact distance was reduced. It seems to be exerting influence on the stability of the pig inside the pipe, so it needs to be increased. Another modification is the absence of a flat spring, originally located inside the track gutter, which would be responsible for amplifying the contact force.

The control system is in development and the idea is to include a mechanical control unit for each track. However, the first laboratory test showed that the tool is very strong and has a great potential.

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