ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

ANALYSIS OF CONTACT FORCES ACTING UPON PIPELINE PIGS

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Abstract. *Pipeline pigs are devices that are inserted into and travel throughout the length of a pipeline driven by a product flow. They were originally developed to remove deposits that could obstruct or retard flow through a pipeline. Today pigs are used during all phases in the life of a pipeline for many different reasons. This work is concerned with numerical modeling of the unilateral contact problem involving low stiffness structures (pig cups) and a rigid surface (pipe wall). The Finite Element Method is applied in the discretization of the structure. The unilateral contact problem is approached to a quadratic optimization problem with inequality linear constraints, whereas the objective function is the total potential energy of the elastic structure. The solution of the proposed problem is by means of an active set strategy or projection method. The obtained numerical results are compared with numerical and experimental data.*

Keywords: pig, pipeline, contact, optimization

1. INTRODUCTION

The pig is a device which can be defined as "a projectile through a pipe driven by hydraulic or pneumatic pressure, maintaining some type of positive seal with the wall of the tube" (O'Donoghue, 1993). It was developed as a solution procedure for the mechanical removal of paraffin deposits and encrustations in existing pipelines used to transport oil and oil products.

The pigs are classified according to their functions: conventional and instrumented. The conventional are the ones which perform the basic functions of removing solid and liquid separation of dissimilar products, while instrumented pigs are equipped with sensors which has the function of monitoring certain parameters of the pipe (Lino et al, 1992 and Gomes, 1994).

Although the use of pigs has become a routine procedure in the oil and gas, and more recently, the water utilities in large cities, there is still a lack of reliable tools for predicting the main variables related to movement of the pig through pipe (Campo, 1998).

The most concerning issue in a release of a pig is the locking that occurs when the sum of frictional forces overcomes the force of propulsion, resulting in the interruption of production and the difficult task of removal. Thus, for safe operation with pigs must be known: the minimum pressure to start movement of the pig, the minimum pressure to overcome an obstacle, and the pressure to the pig´s destruction (Lino et al, 1992). This information is not available in the open literature because of it's high strategic value, and the high costs and difficulties involved on obtaining these data that are generally experiments performed in test circuits.

Among the first works found about the contact forces acting on the pigs there are Saevik and Soreide (1988), and Varvelli and Romagnoli (1991) that aimed on determining the differential pressure for early movement of the pig. These models used the Finite Element Method coupled with an iterative routine to search the starting pressure.

In 1993, O'Donoghue presented a study where the problem of contact between the pig and the pipe was analyzed using a theoretical model based on the sealing technology, and in parallel an extensive experimental program was developed. Their results have became the benchmark in the study of the behavior of the pig, and validated the main assumptions made by and Saevik Søreide (1988), and Varvelli and Romagnoli (1991).

Gomes in 1994 analyzed the contact forces and deformations of cups of seven different pigs through a numerical model using the finite element method and performed the comparison with the results of racing pigs in test circuits. The output of the model Gomes were consistent with those obtained experimentally and with those found by O'Donoghue (1993).

Analyzing only the contact problem is necessary to highlight the work of Givoli and Doukhovni (1996) and Kontoleon and Baniotopoulos (2000), who used the finite element method in conjunction with algorithms Quadratic Programming getting good results.

This study aimed to implement a simple model, consistent with the physical reality of the problem and develop a computational numerical model using the Finite Element Method and Quadratic Programming algorithm for analyzing

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the contact forces acting on the pig, and verify its moving start condition by comparing the results with those obtained experimentally and numerically by Gomes (1994).

2. CONTACT PROBLEM DESCRIPTION

To analyze the contact forces acting on pigs, it is necessary to have a general understanding of their behavior in the pipe. Initially, the device is inserted into the pipe remains motionless, and then starts the pumping of fluid behind the pig generating a pressure differential Δp. This differential grows until it is sufficient to overcome the resistive forces, thus initiating the movement of the pig.

In order to obtain a better efficiency in sealing and cleaning operation cups pig must have a structure of low rigidity and high resilience, which can be achieved by acting on the geometric configuration and constituent materials of the cups, Overall elastomers which has the features as high resilience and resistance to tearing and abrasion (Gomes, 1994). Also with respect to form, the nominal diameter of the pigs is slightly larger than the pipe, and interference between these surfaces generates a loading surface perpendicular to the contact interface, called interference load ($\mathbf{F_{c\ int}}$) responsible for forming cup pig along the wall of the pipe (Fig. 1).

The pressure differential Δp produces the inner surface of cup pig load surface normal ($\mathbf{F_{sn}}$) that further compresses the pig against the pipe wall. As a consequence, there is increased contact area and modification of surface loading normal to this area by the appearance of a new contact load, called load operation ($\mathbf{F_{c\ \Delta p}}$). The resulting loads and operating interference is responsible for sealing the pig and is called normal contact force ($\mathbf{F_c}$).

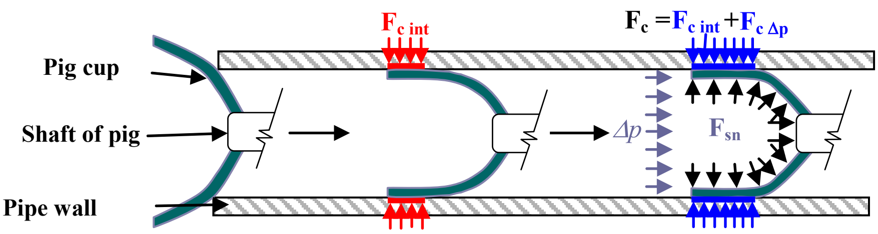

Figure 1. Normal contact force due to interference and pressure differential

In response to the resulting axial load applied to the pig $\mathbf{F_{sn}}$, there are forces which arise in the direction tangent to the surface area of contact, which are directly related to the relative speed of the pig and the lubrication regime of the problem, and may be of Coulomb type, caused by direct contact between the surfaces, and hydrodynamics, caused by fluid flow in the contact interface. These tangential forces in conjunction with the normal forces are the contact forces acting on the pig and are fundamental to the analysis of their behavior inside the pipe.

Considering the analysis of the problem of contact between the pig and the wall of the pipe, the pig is considered perfectly elastic and the pipe a rigid wall, and adopting a reference system RΘZ positioned so that the Z axis coincides with the axis of symmetry of the tube and pig according to the (Fig. 2).

The undeformed profile cup pig can be expressed by it's radial coordinate $\mathbf{r_p}$ that varies with the axial coordinate z, and the profile of the inner wall of the pipe by the radial coordinate $\mathbf{r_t}$ which is constant in this system (Fig. 2). The gap that would occur between the outer surfaces of the pig and the inside wall of the pipe, if the pig remained undisturbed inside the pipe, is provided by the difference between the radial coordinates $\mathbf{r_t}$ and $\mathbf{r_p}$, being called gap in undeformed condition h_i Eq. (1).

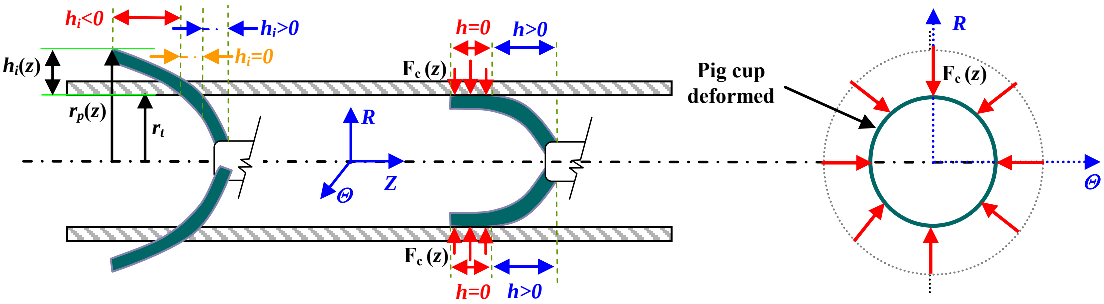

Figure 2. Analysis scheme of pig in both deformed and undeformed conditions

$$h_i(z) = r_t - r_p(z) \tag{1}$$

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Stepping through to the outer surface of the cup pig undeformed condition is verified that the clearance can display three cases: i) $h_i > 0$, indicating that the surfaces are not in contact, since there is a gap between them, ii) $h_i = 0$, indicating that the surfaces are in contact, and iii) $h_i < 0$, indicating that the pig's cup reach the limits of the contour of the pipe wall.

However, the physics of the problem is valid only in the first two cases are valid, that is, the gap should be always zero or positive. And gap in the deformed state can be obtained from the expression of gap at undeformed condition (h_i) adding the ū parameter corresponding to the radial displacement that the cup must undergo to the equilibrium conditions and kinematic restriction of non negative negative gap be respected.

$$h(z) = r_t - r_p(z) - \bar{u}(z) \qquad h(z) \geq 0 \tag{2}$$

The inequality in the formula shown above expresses the condition of non-interpenetration between the surfaces of the pig and the pipe wall.

The normal contact forces (**F**$_c$) acting on the cup pig and the pipe wall are compressive, they have a direction opposite the normal vector (**n**) on the surface in question. Considering the contact area of the pig, this normal vector (n_{pig}) has the same direction as the radial axis R, thus the contact forces acting on the pig will be negative in the region of contact and zero when outside this region being represented by expression Eq (3).

$$F_c(z) \leq 0 \tag{3}$$

To fully characterize the contact unilateral constraint is necessary to satisfy conditions beyond the inequality gap and normal contact force. The condition of zero scalar product of these vectors (Simunovic and Saigal, 1995 and Kontoleon and Baniotopoulos, 2000) presented in Eq. (4) also needs to be satisfied.

$$\mathbf{F_c}(z) \cdot \mathbf{h}(z) = 0 \tag{4}$$

This condition is clearly the problem of physical contact, as occurs when the contact surfaces between the contact forces appear normal, however the gap becomes zero, and when the surfaces are non-contact, the clearance takes positive values and the normal contact force is zero.

3. PHYSICAL MODELING

From the understanding of the physical nature of the problem, a set of hypotheses is taken in place that allow obtaining an idealized model that can be solved which in the present study are:

a) Analysis of pig about to move: permits the disregard of inertial forces, and still allows to obtain the minimum pressure differential required for the initiation of movement of the pig;

b) Total sealing contact between the pig and pipe wall: according to studies conducted by O'Donoghue (1993) in static conditions the pig serves as a great sealant;

c) Model with a cup: as whether to perform a static analysis of the problem of the pig, it is reasonable to adopt a simplified model with a cup, disregarding the inertial effects of the pig, this case will be considered the rear cup, which is subject the surface loading due to differential pressure in the pipeline (Gomes, 1994);

d) axisymmetric Problem: Studies by O'Donoghue (1993) indicates that while the pig moves within the inclined pipe the rear cup tends to remain aligned with the axis of the tube thus a model considering only the rear cup can be axisymmetric analyzed as a problem;

e) the cup material with linear elastic behavior: Studies by O'Donoghue (1993) and Gomes (1994) show that if the interference are within the usual range empirically determined, the level of deformation is restricted to the first linear section of the curve elastomer material, ie, the cups exhibit linear elastic behavior;

f) the pipe wall as a rigid body: Because of the high rigidity that the pipe wall has in comparison with the cup pig can be considered that the contact between these surfaces only the cup undergoes deformation, while the pipe wall acts as a rigid wall (Gomes, 1994) and

g) Coulomb Friction: Experimental results indicate a mixed lubrication regime between the pig and the wall of the pipe (O'Donoghue, 1993 and Andrade, 2002) where forces work together Coulomb friction and viscous. However, consideration of only the frictional forces Coulomb is possible and acceptable, provided that they are accepted hypotheses problem axisymmetric, the imminent movement and sealed in full contact interface, characterizing the absence of fluid flow through the region of contact and therefore viscous friction forces.

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4. MATHEMATICAL MODELING

The contact problem of the pig presents an intrinsic nonlinearity due to the mutual dependency between the contact force and gap. In addition, two other nonlinearities may occur, due to one constituent nonlinear elastic behavior elastomers to exhibit large strains, and a geometric associated with large radial displacements suffered by the cup due to interference and movement of rigid body that can pig present inside the pipe.

For this reason obtaining the analytical solution to the problem of contact surfaces conforming becomes extremely difficult and thus were proposed procedures, which approximate solution, can be found in a number of papers published in the last decades, such as Givoli and Doukhovni (1996), and Kontoleon Baniotopoulos (2000) and Barbosa et al (1997).

Most of these procedures using the Finite Element Method (FEM) together with another mathematical method for the specific problem of contact, the most useful: Gap Element Method, the penalty function method and the method Quadratic Programming (Givoli and Doukhovni, 1996) and (Kontoleon and Baniotopoulos, 2000).

In Gap Element Method, a special finite element with adjustable rigidity is inserted into the contact interface, and through the location of the element the clearance between the surfaces is calculated. This method is simple and easy programming, it has been used in several commercial finite element programs, such as NASTRAN and ANSYS. Its biggest shortcoming is the lack mathematical proof and guaranteed convergence, particularly in problems with many gap elements (Givoli and Doukhovni, 1996).

On Penalty Function Method, contact restrictions are introduced in the total potential energy functional through a penalty parameter, thus transforming the problem with restrictions in one or a sequence of unconstrained problems. The method is divided in relation to the penalty function in exterior and interior. On the exterior penalty function is made a penalty every time a constraint is violated. In the inner penalty function or barrier function the penalty is set in order to prevent the violation of restrictions. The deficiency of the method is the penalty parameter inserted into the energy functional, for every penalty term grows and can lead to a bad conditioning of the problem, ie, the non-convergence to the solution or the premature termination of the search (Bazaraa et al, 1979).

The Quadratic Programming method is a viable method of directions where the constraints imposed by contact problem are not violated during the iterative process (Andrade, et al Bazaraa 2002 and 1979), which means that no physical interpenetration between the surfaces occurs. The method starts with a kinematically admissible configuration, and generates new configurations also admissible while respecting the constraints of contact to reach the numerical convergence (Andrade, 2002). One limitation is the fact that the problem must be linear, since the total potential energy function have to be quadratic, but non-linearity on the contact unilateral constraint is introduced into the problem through Lagrange multipliers, which can be associated with normal contact forces.

Given a linear elastic structure under the action of external loads and subject to prescribed boundary conditions, the Principle of Minimum Potential Energy states that "Of all the displacement fields that satisfy the boundary conditions prescribed, the correct state is one that makes the potential energy of the structure minimum" thus making the first variational functional potential energy (π) equal to zero, the balance condition of the structure is achieved.

The total potential energy functional is obtained from the elastic deformation energy of the frame (U) and the work done by the external forces (W):

$$\pi = U - W = \frac{1}{2}\int_V \boldsymbol{\varepsilon}^T \mathbf{C}\,\boldsymbol{\varepsilon}\, dV - \left[\int_V \mathbf{u}^T \mathbf{f}_V dV + \int_A \mathbf{u}_A^T \mathbf{f}_A dA + \sum_i \mathbf{u}_i^T \mathbf{f}_i \right] \tag{5}$$

where ε is the strain tensor, C is the elastic matrix structure and the term in brackets is the work due to body forces, surface and concentrated loads, respectively.

After de discretization of the structure by the finite element method it's possible to obtain the equilibrium condition of the entire structure by the sum of integrals for all elements m the structure, thus:

$$\sum_m \left[\int_{V^{(m)}} \delta\, \boldsymbol{\varepsilon}^{(m)^T}\, \mathbf{C}^{(m)}\, \boldsymbol{\varepsilon}^{(m)}\, dV^{(m)} \right] = \sum_m \left[\int_{V^{(m)}} \delta\, \mathbf{u}^{(m)^T}\, \mathbf{f}_V^{(m)} dV^{(m)} + \int_{A^{(m)}} \delta\, \mathbf{u}_A^{(m)^T}\, \mathbf{f}_A^{(m)} dA^{(m)} \right] + \sum_i \delta\, \mathbf{u}_i^{(m)^T}\, \mathbf{f}_i^{(m)} \tag{6}$$

And in matrix terms, the equilibrium equation of the structure can be summarized as follows:

$$\mathbf{K}\hat{\mathbf{u}} = \mathbf{F}_V + \mathbf{F}_A + \mathbf{F}_L = \mathbf{F} \tag{7}$$

From the analysis of the problem of contact of the pig appears that the contact unilateral constraint to be respected to prevent interpenetration between the surfaces of the pig and the pipeline, thus the equilibrium condition of

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the pig can be obtained from the minimization of the functional total potential energy of π, subject to the restrictions of contact.

Applying equation of not negative clearance (Eq. (2)) in each node outer contour of the pig obtains the discretized expression for the gap **h**, so:

$$h_{n_c} = r_t - r_p^{(n_c)} - u^{(n_c)} \tag{8}$$

where $n_c = n_{c1}, n_{c2}, ..., N_c$ are the nodes of the outer contour of the pig, and grouping the gaps h_{nc} in matrix form makes:

$$\mathbf{h} = \begin{Bmatrix} r_t - r_p^{(n_{c1})} \\ r_t - r_p^{(n_{c2})} \\ \vdots \\ r_t - r_p^{(N_c)} \end{Bmatrix} - \begin{Bmatrix} u^{(n_{c1})} \\ u^{(n_{c2})} \\ \vdots \\ u^{(N_c)} \end{Bmatrix} = \mathbf{b}^{(n_c)} - \mathbf{u}^{(n_c)} \qquad \mathbf{h} \geq \mathbf{0} \tag{9}$$

which can be expressed in terms of the nodal displacements of the whole structure û, by:

$$\mathbf{h} = \mathbf{b} - \mathbf{A}\hat{\mathbf{u}} \tag{10}$$

where the matrix **A** selects the displacements of the nodes of the outer contour of the pig. Thus, the equilibrium condition of the discretized structure can be written as follows:

$$\begin{aligned} &\textit{to minimize} \ : \ \pi = \tfrac{1}{2}\hat{\mathbf{u}}^T \mathbf{K}\hat{\mathbf{u}} - \hat{\mathbf{u}}^T \mathbf{F} \\ &\textit{given} \ : \quad \mathbf{A}\hat{\mathbf{u}} - \mathbf{b} \leq \mathbf{0} \end{aligned} \tag{11}$$

And through the technique of Lagrange multipliers it's possible to introduce the contact condition in functional unilateral total potential energy of π. To this must be transformed to an inequality constraint equal, which is accomplished by variable air gap (Bazaraa et al 1979) which in this case is the proper clearance **h**, thereby obtaining the extension of the Lagrangian function of total potential energy π*:

$$\pi^* = \pi + \boldsymbol{\lambda}^T(\mathbf{A}\hat{\mathbf{u}} - \mathbf{b} + \mathbf{h}) \tag{12}$$

And the equilibrium condition of the problem is obtained by δπ* = 0:

$$\begin{cases} \mathbf{Ku} - \mathbf{F} + \mathbf{A}^{\mathbf{T}}\boldsymbol{\lambda} = \mathbf{0} & (13) \\ \mathbf{A}\hat{\mathbf{u}} - \mathbf{b} + \mathbf{h} = \mathbf{0} & (14) \\ \boldsymbol{\lambda}^{\mathbf{T}}\mathbf{h} = \mathbf{0} & (15) \\ \boldsymbol{\lambda} \geq \mathbf{0} & (16) \\ \mathbf{h} \geq \mathbf{0} & (17) \end{cases}$$

By Equation (13) shows that **λ** has dimension of force, since the matrix **A** is dimensionless. Equation (14) expresses the equality constraint necessary to enable the introduction of unilateral contact condition in the energy functional via Lagrange multipliers. In Equation (15) is that the dot product of force **λ** by the clearance variable **h** is zero, so one two cases may happens:

1) h > 0: indicates that the surfaces are not in contact as soon **λ** must be zero to satisfy the condition.

2) h = 0: indicates the contact between the surfaces, if **λ** is null has the trivial solution, so **λ** should be positive.

It can thus be seen that the vector **λ** relates directly to the normal contact forces because it acts only in the region where the clearance is null. It's meaning is given based on the body that is acting, because as seen in physical modeling has compressive character, taking the opposite direction of the surface normal vector in question.

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5. DESCRIPTION OF COMPUTATIONAL NUMERICAL PROCEDURE

The numerical solution procedure can be basically divided into three phases: the first is the discretization of the problem, the second is the minimization of the energy functional and the third is checking the condition of motion.

1) Discretization Problem: basically consists of three steps, meshing, assembly of arrays of finite elements, and discretization of loading and contact conditions.

2) Minimization of energy functional: initially the functional potential energy of the problem (π) is mounted from the global stiffness matrix **K** and the vector to force $\mathbf{F_A}$, and then carried out the minimization of the functional subject to the condition nonnegative gap, getting a problem analogous to condition expressed by Eq (11). The method used to solve the problem is a strategy of active sets, also known as projection method analogous to that described by Bazaara et al (1979), and basically consists of two phases: first involves determining an viable initial condition if any, and the second step involves the generation of a sequence of viable points that iteratively converge to the solution. A feasible point is one that respects the restrictions imposed in the case of pig $h > 0$. In response there are the nodal displacements that lead to structure the condition of minimum and the Lagrange multipliers that are associated with normal contact forces.

3) Movement Condition Verification: From the beginning of normal contact forces and the assumption of Coulomb friction it is possible to evaluate if the resulting surface forces acting on the pig in the axial direction is able to overcome the resistive forces of Coulomb, given by the product between the coefficient of static friction and the resulting normal contact forces. Thus, the equilibrium condition in the axial direction or the condition of movement of the pig can be expressed by

$$\Delta F_z(\Delta p, \Delta r) = \Delta p\, A_t - \mu\, F_c \geq 0 \tag{18}$$

Where: ΔF_z is the resultant of forces in the axial direction, Δp is the differential pressure in the pipeline, Δr is the interference between the pig and the pipe, At is the cross-sectional area of the pipe, μ is the coefficient of friction Coulomb and F_c is the resultant of normal contact forces.

When the result is positive the pig is moving, when the pig is still negative and zero indicates when the condition of imminent movement.

A widely used procedure to obtain this differential is the incremental process where each iteration of the minimization of the energy functional checks the condition of movement, if not, it increments the pressure differential of a pre-set value and again performs the minimization. The process is repeated until it is the condition that the imminence or pig from moving.

There are several procedures for determining an end point of a function, in general the most efficient are those using the gradient of the function under consideration, since this provides the greatest growth direction of the function. In case the condition of motion (Eq. (18)) the functional relationship between the total normal contact forces (F_c) and the differential pressure in the pipe (Δp) is unknown which prevents the use of techniques based on gradient but in these cases there are several optimization methods without use of derivatives, as shown by Bazaraa et al (1979) and this work we used a procedure analogous to that described by Zhu et al (1993) and Andrade (1997), known as the criterion sub-relaxation, thus:

$$p^{k+1} = p^{k-1} + \alpha(p^k - p^{k-1}) \tag{19}$$

where:

p^{k+1} is the pressure differential in the next step

p^{k-1} is the pressure differential of the current step

is the differential pressure is obtained by the condition of motion

α is the sub-relaxation factor, which in general is obtained analytically for each type of problem, but here will be taken as constant, in the same manner as shown by Zhu et al (1993) and Andrade (1997) and was used in implementations value of 0,9.

The procedure displayed by the algorithm of Figure 3 follow the steps:

1) enter the value of the differential pressure p^{k-1}

2) Perform the minimization of the total potential energy functional (π) and obtain the contact forces normal for this configuration.

3) Verify the condition of movement of the pig, if so terminating the procedure if negative go to the next step.

4) is attributed the value of

5) Calculate the pressure differential of the next step $p^{k+1} = p^{k-1} + \alpha(p^k - p^{k-1})$ and returns to the first step making $p^{k+1} = p^{k-1} + \alpha(p^k - p^{k-1})$

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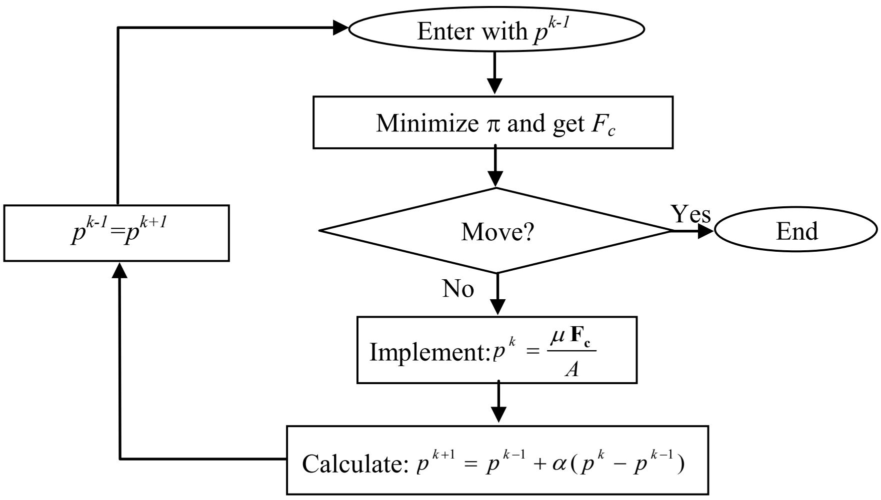

Figure 3. Initial differential pressure search algorithm

6. NUMERICAL PROCEDURE APPLICATION

Gomes (1994) in his dissertation determined the minimum differential pressure required to initiate movement of the pig Vantage, by applying incrementally differential pressure in the pipe. In order to verify the consistency of their results and validate their solution model, experimental tests were performed on a circuit of pipes mounted on the Petrobras Research Center (CENPES). The geometric configuration of the section of the rear cup of the revolution pig Vantage has it's dimensions given in the figure below:

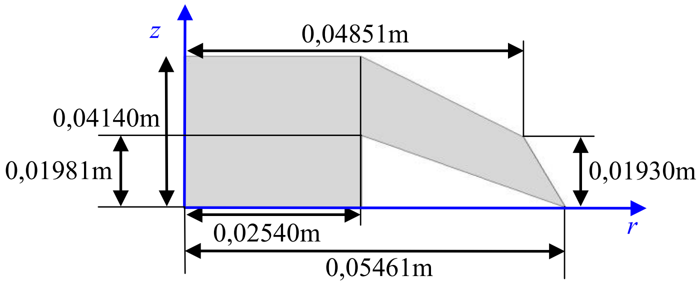

Figure 4. Geometrical configuration of a revolution section of Vantage's Pig cup

The data of the problem are: Radius of Pipe (r_t): 0,04861 m, Modulus of Elasticity (E): 15,2 MPa, Poisson's ratio (ν): 0,42 , and Coulomb friction coefficient (μ) : 0,48.

The pressure differential obtained by starting the experiment was 2,69 x10^5 Pa, and the results obtained numerically by Gomes and models of this study are:

Table 1 – Numerical results of Advantage pig's initial differential pressure

	Initial Differential Pressure	Percentual Error
Gomes Numerical Model	3,38 x10^5 Pa	+ 25,65 %
Implemented Numerical Model	2,60 x10^5 Pa	- 3,35 %

The procedure implemented based on a numerical optimization method without use of derivatives known as the criterion sub-relaxation (Zhu et al, 1993 and Andrade, 1997) was shown to be very effective in evaluating the pressure differential basis for the pig Vantage, with absolute percentage error of 3.35% against 25.65% obtained by the numerical model of Gomes (1994).

The graphs in Figure 5 show the geometric configurations of the pig Vantage undeformed conditions and imminence of movement and the profile of the distribution of contact forces also in the normal start condition the pig.

Analyzing the results of numerical and graphical deformation cup pig and the profile of normal contact forces, it is possible to verify the consistency of the procedure quantitatively and qualitatively solution for determining the starting differential pressure and contact forces operating in normal pig Vantage.

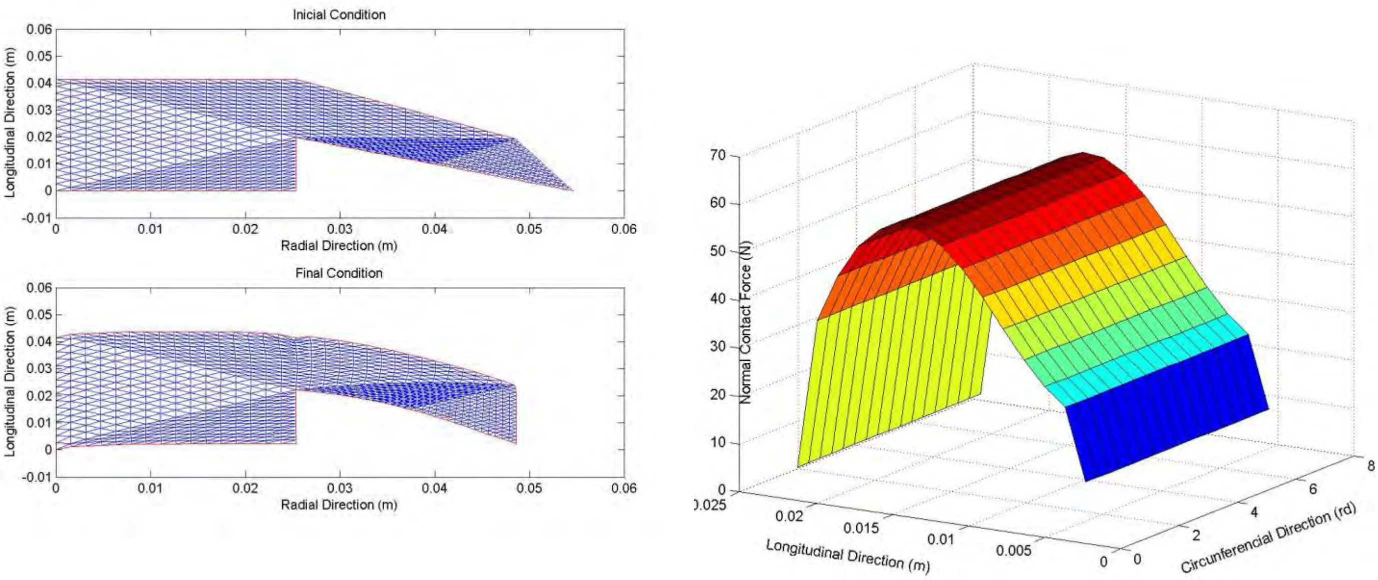

Figure 5. Geometric configurations of the pig in undeformed conditions and imminent motion and the contact forces profile in the normal condition of pig Vantage

7. CONCLUSIONS

In the present study a simple model implementation was conducted and is consistent with the physical reality of the problem, and a computational numerical model was developed using the finite element method, and a Quadratic Programming Algorithm for analysis of contact forces acting on the pig, checking start condition of the movement, and comparing the results with those obtained experimentally and numerically by Gomes (1994).

Initially the physical modeling about the contact problem between the pig and the pipe wall was carried out, adopting a set of viable hypotheses allowing the equation and solving the problem.

The mathematical modeling was performed using the finite element method in conjunction with the Quadratic Programming Method, in which the restrictions imposed by the contact problem are not violated during the iterative process (Andrade, 2002 and Bazaraa et al, 1979), and the nonlinearity concerning the restriction was introduced in an unilateral contact problem by the Lagrange multiplier, which can be associated with normal contact forces.

The numerical solution procedure was divided into three phases: the discretization problem of minimizing the energy and functional verification of the condition of motion. To obtain the pressure differential was used an incremental process where each iteration there is a condition of movement, if not, it increments the pressure differential of a pre-set and again executes the process until that meets the condition of imminent or that the pig enters into motion.

The results obtained through the proposed study showed consistency for the quantitative and qualitative determination of differential pressure starting and normal contact forces acting on the pig Vantage, getting an absolute percentage error of 3.35% compared with 25.65% obtained from the model Numerical by Gomes (1994) in relation to the experimental results.

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