XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Analysis of free-spanning pipelines using design of experiments techniques

Matheus A. Miranda[1], Renato R. L. Santos[1], Josué D. S. Neto[1], Emerson A. F. Santos[1], Eduardo S. S. da Silveira[1]

[1]*Laboratory of Scientific Computing and Visualization, Federal University of Alagoas*
Av. Lourival Melo Mota s/n, Cidade Universitária, CEP: 57072-900, Maceió/AL, Brasil
matheus.miranda@ctec.ufal.br, renato.ramos@lccv.ufal.br, josue.neto@lccv.ufal.br, emerson_acacio@lccv.ufal.br, eduardosetton@lccv.ufal.br

Abstract. The discovery of new oil and gas fields in offshore regions, increasingly distant from the coast, required the use of pipeline systems increasingly extensive and exposed to more hostile environments. Due to irregularities in the seabed and the length of the pipes, the occurrence of free spans, when the pipe loses contact with the ground and is suspended, and the phenomenon of Vortex-Induced Vibrations (VIV) are greater, which can decrease the system life. Thus, the analysis of free spanning pipelines is necessary for the design of the systems, which normally requires numerical simulations. However, to reproduce the behavior of the pipe, a set of parameters, that are not easily or precisely determined, is requested often demanding parametric studies that require countless numerical simulations. In this way, this work has the objective of using techniques of design of experiments (DOE) in order to improve the structural analysis of pipelines in free spans. The application of design of experiments techniques allows to verify which parameters are most significant for the problem. Therefore, it is expected that the design variables determined from the design of experiments will present accurate responses and the numerical simulation process will be optimized.

Keywords: VIV, Free span, Pipeline

1 Introduction

The use of submarine pipeline systems for the transportation of oil-derived hydrocarbons in offshore regions has proved to be reliable due to the capacity to adapt to hostile environments and more remote locations, according to Lima [1].

However, the expansion of oil and gas fields in these regions exposed the pipelines to situations called free spans, where some of their parts are not in contact with the seabed, being susceptible to loads caused by vortex-induced vibrations (VIV), which can shorten the life of the pipeline, according to Santos [2].

Thus, the structural analysis of free-spanning pipelines becomes increasingly relevant, as well as the knowledge of the parameters that most contribute to the phenomenon of VIV, which normally requires a high number of numerical simulations. The use of Design of Experiments (DOE) techniques is an alternative for reducing the number of required simulations. As shown in Montgomery, Runger and Calado [3], when using DOE techniques, it is possible to determine which variables or parameters of a process are most influential in relation to one or more variable responses through statistical tests, which makes it possible to increase the process yield, a less variability and reduced development time.

The objective of this work was to perform a parametric study of some design variables of a submarine pipeline using DOE techniques aiming at the knowledge of the set of most influential variables in the structural behavior of subsea pipelines, improving the analysis with application in future studies.

2 Methodology

For the modeling of the pipe and loads, the commercial finite element software Abaqus® [4] was used and to integrate the simulation files and apply the DOE techniques, the commercial software Isight® [5]. Both softwares are marketed by SIMULIA®, a brand of the company *Dassault Systèmes*.

The Python programming language (Van Rossum and Drake Jr. [6]) was used to implement functions in order to automate the simulation process in the following steps:

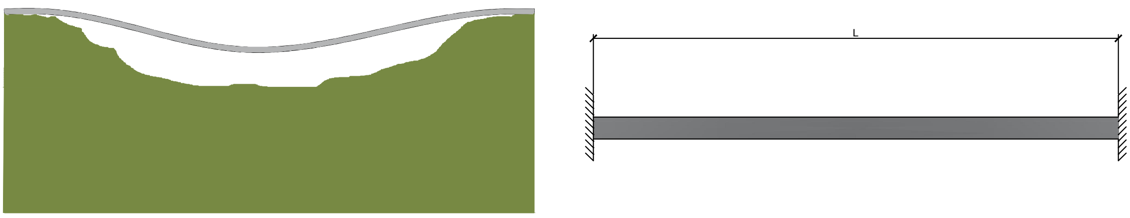
- Write input file to Abaqus®;
- Providing the required parameters for DOE processes;
- Run the simulations;
- Extract the requested results.

The free-spanning pipeline was modeled as a beam fixed at both ends as provided in DNVGL-RP-F105 [7]. The loads included in the model were internal pressure, external pressure and self weight, which depend on certain characteristics, such as the geometry of the pipe and the depth in which it is located. The fixed parameters, that is, that were not considered for DOE techniques, and their respective values are shown in Table 1.

Table 1. Fixed model parameters

Parameter	Value
Thickness of anticorrosive coating (m)	0.01
Thickness of coating (m)	0.07
Poisson's ratio	0.30
Density of anticorrosive coating (kg/m³)	910.00
Density of coating (kg/m³)	700.00
Density of seawater (kg/m³)	1025.00
Density of internal fluid (kg/m³)	916.00
Operating pressure (Pa)	14.71×10^6
Water column (m)	500.00
Reference height (m)	10.00

Figure 1 shows an illustrative diagram of a free-spanning pipeline and the adopted model.



(a) (b)

Figure 1. Illustrative diagrams: (a) Free-spanning pipeline (b) Adopted model

As see in Montgomery [8], a empirical model for DOE is an equation between design factors and response. One of the most used model is the first-order model, also called main effects model. A first-order model in two variables is shown in eq. (1),

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon, \quad (1)$$

where y is the response, x's are the design factors, β's are coefficients which are estimated from the data in the experiment and ε is a random error which justifies the experimental error in the process studied. A usual enlargement of the main effects model is to add interaction terms. This model is widely used because the interaction effects between factors is relatively common. Another empirical model used in optimization experiments is the second-order model. A second-order model in two variables is shown in eq. (2),

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon, \tag{2}$$

where $\beta_{12} x_1 x_2$ is the two factor interaction term (above-mentioned) and the second-order terms are represented by $\beta_{11} x_1^2$ and $\beta_{22} x_2^2$

For DOE analysis, the following processes were selected in Isight ®: full factorial, fractional factorial and latin hypercube sampling. The importance of factorial designs is presented by Cunico et al. [9] while the Latin Hypercube Sampling method was proposed by McKay et al. [10]. Five pipe parameters were considered as factors for the application of the techniques, with each factor being able to occupy 3 distinct levels, which are shown in Table 2.

Table 2. Parameters used in DOE techniques

Level	1	2	3
Density of steel (kg/m³)	7850.00	10000.00	15000.00
E - Young's Modulus (Pa)	200.00×10^9	250.00×10^9	300.00×10^9
Outer diameter - Steel (m)	0.30	0.50	0.80
Thickness - Steel (m)	0.03	0.05	0.08
Span length (m)	25.00	50.00	100.00

The response variable analyzed through DOE was the effective axial force in the middle of the free span. According to DNVGL [7], the effective axial force (S_{eff}) is defined by eq. (3),

$$S_{\text{eff}} = N_{\text{tr}} - p_i \cdot A_i + p_e \cdot A_e, \tag{3}$$

where N_{tr} is the true steel wall axial force, p_i is the internal pressure, p_e is the external pressure, A_i and A_e are the external and internal areas of the pipeline, respectively. In the finite element analysis, the input file was configured so that each element had the length of an outer diameter of the pipe as provided in DNVGL-RP-F105 [7].

3 Results

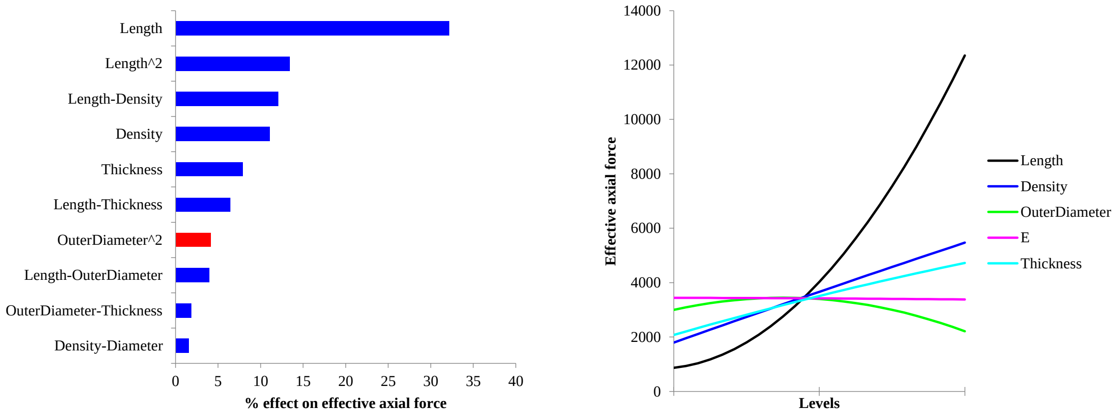
The results of the techniques are shown in Pareto charts and main effect plots. A Pareto chart or diagram is used to order the factors of an experiment according to their frequency of occurrence, while a main effects plot provides the average response for each level of the analyzed factor.

Figure 2 presents the results of the Full Factorial technique, which required 243 simulations.

Figure 3 presents the results of the Fractional Factorial technique using the 1/3 fraction, which required 81 simulations.

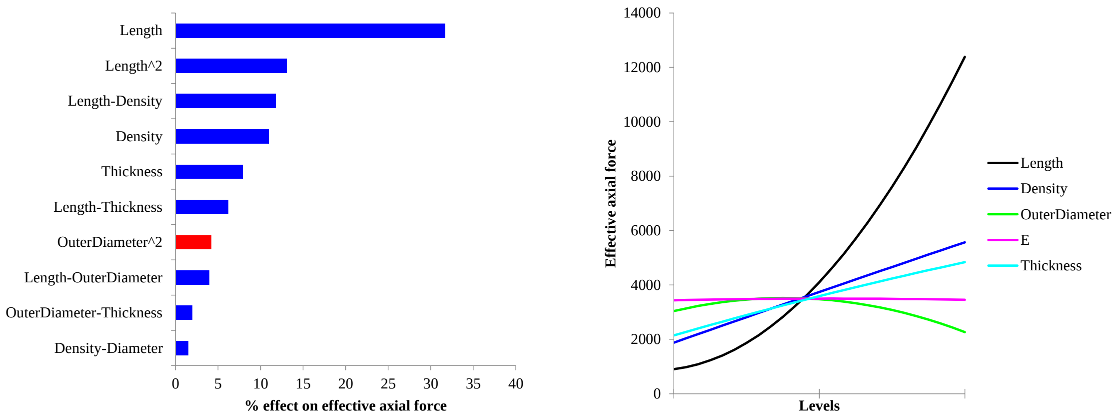
Figure 4 presents the results of the Latin Hypercube Sampling technique. This process selects a random sample of combinations between the factors and approximates the results of the Full Factorial technique with the increase in the number of combinations chosen. In this study, 122 combinations were selected, approximately half of all possible combinations, assessed using the Full Factorial technique.

Comparing the results of processes used, the similarity between them was clear. The Full Factorial and Fractional Factorial methodologies showed basically identical results, while the Latin Hypercube technique showed certain differences, one of them related to the Young's Modulus. These disagreements can be justified by the randomness characteristic of the procedure when selecting the parameters of the experiment. The most influential factor in the response was span length according to the three techniques applied, showing a percentage error of 1.4% for Fractional Factorial and 6% for Latin Hypercube Sampling, both in relation to Full Factorial technique.The effect of interaction between density and length was also highlighted. Consideration of the interaction effects is extremely advantageous, as they can significantly alter the analysis of the results obtained, as seen in Montgomery [8].



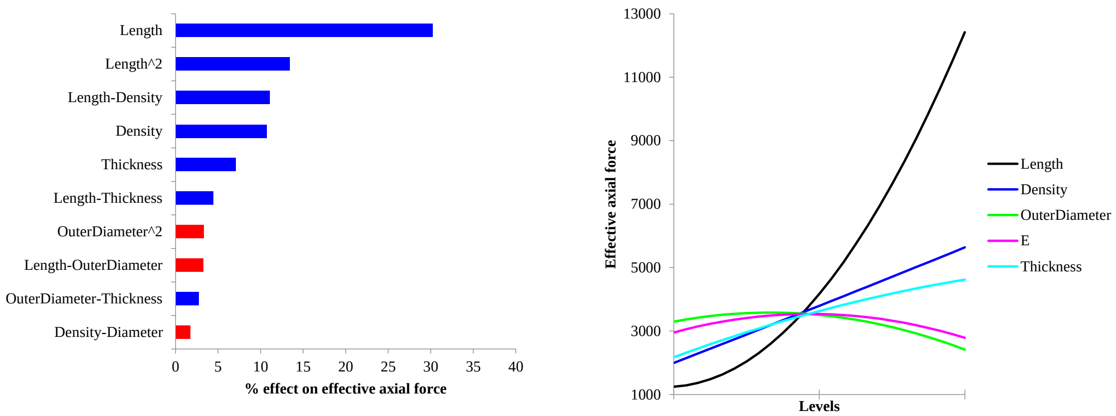
(a) (b)

Figure 2. Results of the Full Factorial technique: (a) Pareto chart (b) Main effect plot



(a) (b)

Figure 3. Results of the Fractional Factorial technique: (a) Pareto chart (b) Main effect plot



(a) (b)

Figure 4. Results of the Latin Hypercube Sampling technique: (a) Pareto chart (b) Main effect plot

4 Conclusions

With respect to the subject above mentioned, it was observed that the span length proved to be the most influential parameter in the value of the effective axial force in the half of the pipeline's stretch in free span, considering the model used.

The application of DOE techniques also shows that some interaction effects related to geometry and pipe material also have more influence than some main effects, highlighting the advantage of the techniques used. It was also noted that the Fractional Factorial and Latin Hypercube methodologies demonstrated results consistent with the Full Factorial with a smaller number of simulations, which reduced the simulation time and the computational cost of the process. As Latin Hypercube Sampling technique selects combinations at random, care must be taken when using it in order to avoid biased results that do not represent the total set of possible combinations.

Therefore, the DOE processes allowed to identify the influence of some design variables in the analysis of free-spanning pipelines, as well as the most appropriate procedures, which can provide compatible results at a lower computational cost.

Acknowledgements. This work was supported by Laboratory of Scientific Computing and Visualization (LCCV), Center of Technology (CTEC), Federal University of Alagoas (UFAL) and National Council for Scientific and Technological Development (CNPq).

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Lima, A. J., 2007. *Análise de dutos submarinos sujeitos a vibrações induzidas por vórtices*. PhD thesis, UFRJ.

[2] dos Santos, M. V. F., 2015. *Um estudo comparativo de dutos em vãos livres através de simulações numéricas*. PhD thesis, Universidade Estadual de Campinas.

[3] Montgomery, D. C., Runger, G. C., & Calado, V., 2000. *Estatística Aplicada E Probabilidade Para Engenheiros* . Grupo Gen-LTC.

[4] Abaqus, S., 2014. *Version 6.14 User's Manual*. Systèmes, Dassault, Providence, RI, USA.

[5] Isight, S., 2009. Isight component guide. *North Carolina, USA: Engineous Software*, vol. 22, pp. 24.

[6] Van Rossum, G. & Drake Jr, F. L., 1995. *Python reference manual*. Centrum voor Wiskunde en Informatica Amsterdam.

[7] DNVGL, 2017. DNVGL-RP-F105 Free spanning pipelines 2017.

[8] Montgomery, D. C., 2017. *Design and analysis of experiments*. John wiley & sons.

[9] Cunico, M. W. M., Cunico, M. M., Miguel, O. G., Zawadzki, S. F., Peralta-Zamora, P., & Volpato, N., 2008. Planejamento fatorial: Uma ferramenta estatística valiosa para a definição de parâmetros experimentais empregados na pesquisa científica. *Visão Acadêmica*, vol. 9, n. 1.

[10] McKay, M. D., Beckman, R. J., & Conover, W. J., 2000. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, vol. 42, n. 1, pp. 55–61.