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Experimental modal analysis of electrical submersible pumps

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ABSTRACT

The dynamic behaviour of an electrical submersible pump (ESP) under operational conditions installed in a test well is investigated by identification of its natural frequency and damping parameters. The study is conducted using an experimental modal analysis technique, the Least Square Complex Exponential (LSCE) method. The excitation was generated at one single point, because of the boundary conditions, by an impact hammer (i.e., single-input, multiple-output, or SIMO, analysis was performed), and the response signals were acquired by accelerometers fixed over the pump housing, thereby characterizing output-only processes. To evaluate the complex exponential function to fit the autoregressive function used to model the impact response function (IRF), auxiliary criteria, the averaged normalised power spectrum density (ANPSD) were used. Results have shown that the ESPs would have natural frequencies within the operational frequency range, from 30 to 62 Hz, leading to the operation in resonance conditions.

1. Introduction

Electrical submersible pumps (ESPs) are applied in the petroleum industry to pump great amount of fluids from subsea deep wells. Currently, ESPs are responsible approximately for 10% of the worlds crude oil production (Takács, 2009). When high flow rates are required, there are two available technologies that can be applied. The first one, the gas lift method, is the most reliable and features low intervention costs in the case of failure. In this method, gas is injected at high pressure in the well production tubing to reduce the fluids specific mass and also drag the liquid to the surface. Both factors act to lower the well bottomhole pressure at the bottom of the tubbing. The second method, which is the main subject of this work, is to increase the fluid pressure that comes from the reservoir using an ESP – Electrical Submersible Pump (Ribeiro et al., 2005).

ESP systems are much more complex and less reliable than the gas lift method, but they are more efficient and able to yield higher flow rates and pressure. However, decide which method to choose relies not just on technical analysis; rather, economic issues must

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Abbreviation: β, Autoregressive Coefficients; Δt, Finite Time Difference; ξ, Damping Factor; φ, Quadratic Mean Value; λ, Characteristic Equation Roots; λ_u, Dynamic Poles in u Mode; μ, Mean Value; Ω, Spectral Frequency rad/s; ω, Spectral Frequency Hz; ω_n, natural frequency; ω_d, Damping Natural Frequency Hz; ω_{du}, Damping Natural Frequency in mode u; ω_u, Natural Frequency in mode u; σ, Result of Multiply Damping Factor and Frequency; τ, Relative Time Shift; θ, phase angle; $\delta(t)$, Dirac Function, Impulse Function; A, Dynamic System Response; a, Real Part of Complex Number; b, Complex Part of a Complex Number; c, Damping Coeficient; Cc, Critic Damping Coeficient; D, Time Serie; e, Euler Number; er, Sample Error; E, Quadratic Error; F, Excitation Force Amplitude; f, Excitation Force Function; F_F, Fourier Transform of $f(t)$; F_L, Laplace Transform of $f(t)$; G, Power Spectral Density Function "Two Sided"; Gr, Number of Degree of Freedom; g, number of Impulse Response Functions; i, Complex Number; K, Stiffness Matrix; k, Index of a Sample of Discrete Time Serie; L, Laplace Transform Operator; M, Mass Matrix; m, mass; N, Number of Points of a Time Serie; n, Sample Index; O, Model Order; p, Number of Degree of Freedom of Excitation; q, Number of Degree of Freedom of Response; R, Phasor Amplitude; r, Transfer Function Residue; r_{pqu}, Residue of a System with Excitation in Point p and Response in q in Mode u; RMS, Root Mean Square; s, Laplace complex frequency; S, Power Spectral Density Function "one sided"; u, Vibration Mode; V_r, Auxiliar Variable; x, Linear Combination of Complex Series; y, Independent Variable; Y_F, Fourier Transform of y; API RP, American Institute of Petroleum Recommended Practice; ANPSD, Averaged Normalised Power Spectrum Density; AR, Autoregressive; ESP, Electrical Submersible Pump; S-ESP, Submarine Electrical Submersible Pump; BEP, Best Efficiency Point; CE, Complex Exponential; CENPES, Centro de Pesquisas e Desenvolvimento Leopoldo Americo Miguez de Mello; DFT, Discrete Fourier Transform; EMA, Experimental Modal Analysis; FAT, Factory Acceptance Tests; FFT, Fast Fourier Transform; FRF, Frequency Response Function; IDFT, Inverse Discrete Fourier Transform; IRF, Impulse response Function; LEDAV, Laboratory Of Dynamic Behaviour and Vibration Analysis; LSCE, Least Square Complex Exponential; LTI, Linear Time Invariant; MGDL, Multiple Degree of Freedom; MIMO, Multiple Inputs Multiple Outputs; NPSD, Normalised Power Spectrum Function; Petrobras, Petroleo Brasileiro S. A. Company; PSD, Power Spectrum Density; SIMO, Single Input Multiple Output; SISO, Single Input Single Output; UGDL, Single Degree of Freedom; VSD, Variable Speed Drive

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be considered. Although greater revenue is provided by the ESP method, its manufacturing and installations costs are very high; consequently, increasing the equipment reliability to reduce the risk of premature failure is a primary goal.

Initially, ESPs had applications only for onshore production. However, because of the pioneering spirit of the petroleum company Petrobras, in 1994, this technology began to be tested in an offshore field, the *RJS* – 221 oil well in Campos Basin, Brazil. In 1998, after only 4 years of development, the company was able to use the method in deep water.

ESPs are normally composed of 3 different sections: a pump, a protector/seal and an electric motor. A typical pump is composed of dozens or hundreds of centrifugal sections of small diameter (typically approximately 4–5 in) that are mounted serially and it rotates in an operational frequency range between 30 Hz and 60 Hz. The pump is coupled to a magnet induction motor, which has a protector/seal assembly and is filled with an insulating fluid that is heavier than water. The electric motor is cooled by the well fluids that pass through the outer motor surface. For subsea systems, the output motor power is commonly greater than 1000 hp. The structure can reach more than 30 m long and the pump can operate in hostile environments with high temperature and in the presence of gas and abrasive fluids. Fig. 1 shows complete ESP systems for onshore and offshore installations.

ESPs are installed inside or near the production well, which means that in offshore ultra-deep water scenarios, maintenance is prohibitive because of the need for expensive and unavailability of rig platforms. Assembly errors and manufacturing defects must be avoided to make the method feasible and avoid premature failure, this goal can only be achieved through rigorous quality control, qualification tests and operations procedures (Roberto et al., 2013).

ESP manufacturers employ factory acceptances tests (FATs), but they do not fully simulate the complete ESP behaviour under real-world operation conditions. Additionally, some tests, that are based on vibration analysis signals, do not detect equipment faults when performed separately because of the low torque applied and different structural boundary conditions. For these reasons, FATs do not guarantee that an ESP system will be sufficiently robust to face the harsh environment of deep-water offshore oil wells.

The development of new test concepts, such as Stack-up and String tests, has allowed manufacturers and end users to have a better understanding of the equipment performance and dynamic behaviour. A Stack-up test consists of mounting an ESP in a water test well to collect its performance data under different operational conditions to measure the pump performance curves and perform a complete equipment vibration analysis. The second test, the String test, consists in a complete ESP system, including a down-hole sensor, variable-speed drive (VSD) and its respective total length of power cable, is mounted in a water test well to analyze electrical, mechanical, performances parameters and dynamic behaviour.

Among all performed tests and collected data, vibration analysis is the most precise for fault detection and prevention and currently is the primary method used to quantify the mechanical quality of ESPs. The most popular vibration analysis method is based on graphical analysis in the time domain (waveform signal) and in the frequency domain (spectrum) through the Fast Fourier Transform (FFT) algorithm. To perform the spectral analysis, a time series for a physical parameter is collected through a transducer and processed using mathematical tools. The FFT algorithm enables visualisation of the signal spectral peak using a graph called a spectrum. The FFT is well known and widely used to analyse the vibration signatures associated with equipment performance. Thus, to evaluate the components amplitudes found in the spectrums, it is used the vibration standard document API11-RPS8 for ESP that classifies ESP vibration severity (API 11RP-S8, 1993).

ESP condition severity criteria were defined based on several ESP vibratory analyses of data collected during Stack-up and String tests. The maximum amplitude peaks were defined according to the spectral component peaks amplitudes, as shown in Fig. 2, in which two velocity amplitudes limits are considered, 0.255 in/pol (0.649 cm/s) and 0.156 in/s (0.396 cm/s).

During the tests, it was noticed that a high peak in sub-harmonic frequency at approximately half the shaft rotation speed appeared and caused a hydraulic imbalance, known as the oil whip phenomenon, which is harmless to the ESP integrity. Because this

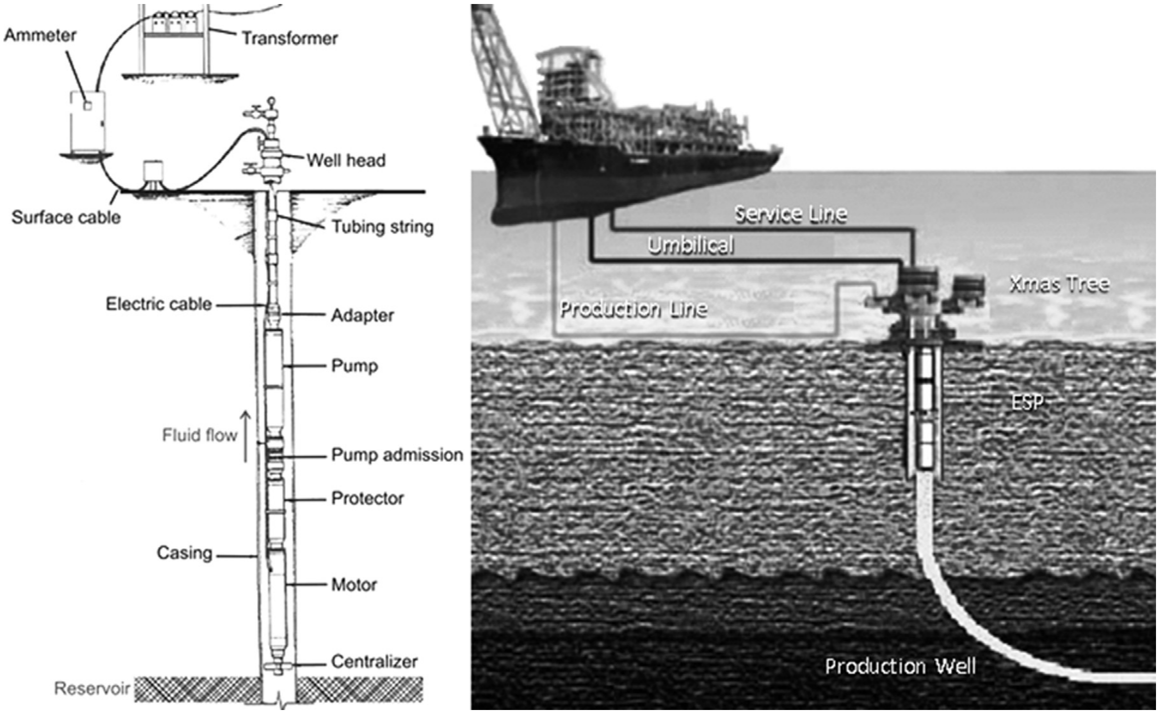

Fig. 1. Onshore and offshore ESP installations.