Simulation Analysis of Critical Contact Load of Buckling Rod in Tubing String

To cite this article: Zhixian Fan et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 242 022028

View the article online for updates and enhancements.
Simulation Analysis of Critical Contact Load of Buckling Rod in Tubing String

Zhixian Fan1,2, Mingming Xing1,2*, Quanzhi Zhou1,2, Kaifeng Xue1,2, Lili Zhou3, Zhiyu Zhang4

1School of Mechanical & Vehicle Engineering, Linyi University, Linyi, Shandong Province, 276000, China
2Municipal Modern Agriculture UAV Engineering and Technological Research Centers, Linyi, Shandong Province, 276000, China
3School of Chemistry & Chemical Engineering, Linyi University, Linyi, Shandong Province, 276000, China
4PetroChina Daqing Oilfield Company, Daqing, Heilongjiang Province, 163000, China

*Corresponding author’s e-mail: xingmingming2009@126.com

Abstract. Sucker rod pumping system is the main equipment of domestic mechanical oil production. The eccentric wear of the rod is the main factor that affects the optimal design of the rod pump system and the reasonable evaluation of pump detection period. Therefore, considering the effect of rod string buckling in tubing, a simulation method for the critical contact load of buckling rod string in tubing is established. In the detail, with double coordinate system method, and the finite element analysis dynamic model of sucker rod string is established. Using ANSYS software, a simulation method for critical contact load of rod string buckling in tubing is established. The simulation results show that the pipe contact stress is affected by the rod string diameter. The maximum stress increases with decreasing the diameter of rod string. The maximum stress of rod string increases with increasing the polished rod load. The effect of polished rod load and rod diameter on buckling stress is considered comprehensively, and the optimum design area of rod string is given. The simulation results have important theoretical and practical for optimal design of sucker rod pumping system and reasonable evaluation of oil well pump testing period.

1. Introduction

At present, pumping unit accounts for about 90% of mechanical pumping equipment, and the proportion of sucker rod pumping system is the biggest. The sucker rod pumping system is used for nearly 80% of China's major oil fields[1]. The sucker rod pumping system has a history of more than 100 years, which is widely used in oil fields all over the world. Although it is long in use and wide in scope, it is a relatively traditional and complex system. In actual production, the underground rod-tube-pump is difficult to observe. The measured date is got difficultly and the maintenance work is difficult to carry out. Therefore, its development is limited. Chief of all, the failure of down-hole rod-tube-pump is the main bottleneck that restricts the development of this system. However, the main failure cause of rod-tube-pump is the eccentric wear of the rod-tube. According to statistics, the oil fields of Shengli has about 13,000 wells, and 85% of them are pumping wells. The number of
eccentric wear of the rod-tube accounts for 30% of the well opening. The eccentric wear of the rod-tube takes up 50~60% of the total oil well maintenance work. Millions of materials are wasted every year [2]. Therefore, this issue is widely concerned by domestic and foreign experts and scholars [3-5]. Relevant data show that 70% of the failure and fracture accidents of the sucker rod occurred at the lower part of the sucker rod string are closely related to the occurrence of the buckling phenomenon of the sucker rod string [6]. Huang gives buckling equation in horizontal wells based on the general buckling and twisting theory of rods [7]. A comprehensive buckling model is derived with fourth-order nonlinear ordinary differential equations by Gao [8]. Han carries on the friction resistance experiment to the phenomenon of the eccentric wear of the rod-tube. The influence of viscous fluid on the sucker rod is measured and the formula of resistance is obtained. Then he points out that the root cause of serious eccentric wear of sucker rod is not entirely caused by the increase of uplift force after polymer flooding [9]. Dong simplifies the inner sucker rod string of the oil pipe to be an eccentrically rotating string, and the influence of eccentrically rotating centrifugal force and axial force on the rod string is considered. The finite element simulation of the mechanical deformation in the tubing is carried out. One of the main reasons for the eccentric wear of rod string in the ground driven screw pumping system is proposed [10]. The influence of the horizontal component and radial force of the sucker rod gravity on the sucker rod string is analyzed by Chang. Then the way to correct the whole well and prevent eccentric wear by means of an encrypted centralizer is proposed [11]. Adoption of the above measures, most oil fields can reduce the damage caused by eccentric wear and increase their production. However, the phenomenon of eccentric wear can still exist and cannot be avoided completely. The simulation results show that the eccentric wear of the rod is related to the critical contact load of the rod string buckling. Therefore, taking the sucker rod-tube as the research object and considering the critical load of the sucker rod string, a method to simulate the buckling of the rod string in oil pumping pipe is established.

2. Mechanical and mathematical models

In this paper, the following assumptions and simplifications are made to the sucker rod string for the convenience of establishing the finite element simulation model of the sucker rod pumping system: The rod string is rigid, which can buckle freely in the direction of the force. The effect of temperature change of rod string is ignored. The axial tension fluctuation and lateral vibration of the rod string are not considered. The influence of centralizer and rod coupling on some parameters is ignored, such as the local cross-sectional area, tensile strength, buckling strength and torsional inertia moment. The radial stress of the rod string and the friction between the rod string and the tubing are considered. The lateral static deformation of the rod string and the friction between the rod string and the tubing are considered. The lateral static deformation of the rod string is studied, and the elastic collision between the rod string and tubing is not considered. The influence of the stiffness of the rod string is considered and the radial deformation of the rod string in the tubing is a nonlinear problem.
The global and local coordinate system of the rod string element is established, and show as figure 1 and figure 2 respectively. Global coordinates XYZ is a fixed Cartesian coordinate system in space. The direction of OX is east. The direction OY is north. The direction OZ is straight up. Well head location is coordinate origin O, and the overall analysis of the sucker rod string will be carried out in this coordinate system.

With figure 1 and figure 2, in the local coordinate system, and each node has a corresponding six degrees of freedom on the space beam element. Therefore, there are six node displacement vectors and six node force vectors. The vector of \( \vec{u} \), \( \vec{v} \) and \( \vec{w} \) is the node displacement vectors along the coordinate axis displacement. The vector of \( \vec{\theta} \) is the Angle around the axis. The vector of \( \vec{X} \), \( \vec{Y} \) and \( \vec{Z} \) is a nodal force vector of axial forces along the axis. The vector of \( \vec{M} \) is the torque around three axes, and the vector of \( \vec{M} \) is bending moment.

The displacement string vector of the element node:

\[
\{ \delta \}^e = \{ u, v, w, \theta_x, \theta_y, \theta_z, u_j, v_j, w_j, \theta_{x_j}, \theta_{y_j}, \theta_{z_j} \}^T
\]

The node force string vector of the element:

\[
\{ F \}^e = \{ X_j, Y_j, Z_j, M_{x_j}, M_{y_j}, M_{z_j}, X, Y, Z, M_{x}, M_{y}, M_{z} \}^T
\]

The displacement function of any point in the space beam element in the local coordinate system:

\[
\{ f \} = [N] \{ \delta \}^e
\]

Where,

\[
[N] = \begin{bmatrix}
1 - \xi & 0 & 0 \\
6(1 - \xi)\eta & 1 - 3\xi^2 + 2\xi^3 & 0 \\
6(1 - \xi)\zeta & 0 & 0 \\
0 & (\xi - 1)\zeta & (\xi - 1)\eta \\
(1 - 4\xi + 3\xi^2)\zeta & 0 & (-\xi + 2\xi^2 - \xi^3)\eta \\
(1 - 4\xi + 3\xi^2)\xi & -(-\xi + 2\xi^2 - \xi^3)\zeta & 0 \\
-\xi & 0 & 0 \\
-6(1 - \xi)\xi \eta & 3\xi^2 - 2\xi^3 & 0 \\
-6(1 - \xi)\xi \zeta & 0 & 3\xi^2 - 2\xi^3 \\
0 & -\xi \zeta & -\xi \eta \\
-2 + 3\xi \xi \eta & 0 & (1 - \xi)\zeta \\
(2 - 3\xi)\xi \eta & -(1 - \xi)\zeta & 0
\end{bmatrix}
\]

Where, \{f\} is the displacement array of any point in the element. \{\delta\}^e is the node displacement array of the element. \{N\} is the form function matrix. \( l \) is length of space beam element. \( \xi \) is x/l. \( \zeta \) is y/l. \( \eta \) is z/l.

The spatial beam element of the sucker rod string has the structural stiffness of tensile, compressive, buckling and torsion resistance. Under axial, torsional and centrifugal inertial loads, the stiffness matrix of the element in local coordinate system can be obtained by the principle of minimum potential energy. Expression:

\[
[K] \{ \delta \}^e = \{ F \}^e
\]
\[
\begin{align*}
\left[ \bar{K} \right]^e &= \left[ \bar{K}_E \right]^e + \left[ \bar{K}_\sigma \right]^e - \left[ \bar{K}_\omega \right]^e \\
\left[ \bar{K}_E \right]^e &= \int \left[ B \right]^T \left[ D \right] [B] \, dx \\
\left[ \bar{K}_\sigma \right]^e &= \rho \int \left[ \left( \left[ N'_2 \right]^T \left[ N'_2 \right] + \left[ N'_3 \right]^T \left[ N'_3 \right] \right) \right] \, dx \\
\left[ \bar{K}_\omega \right]^e &= \rho A \omega^2 \int \left[ \left( \left[ N'_2 \right]^T \left[ N'_2 \right] + \left[ N'_3 \right]^T \left[ N'_3 \right] \right) \right] \, dx
\end{align*}
\]  

(6)

Where, \( \rho \) is beam element density, kg/m\(^3\). \( A \) is beam element cross sectional area, m\(^2\). \( \omega \) is the angular velocity of the rod string, rad/s. \( P_1 \) is Axial tension of the beam element, N. \( \left[ N'_2 \right], \left[ N'_3 \right] \) is the first derivative of the formal function. \( \left\{ \varepsilon \right\} \) is the strain vector. \( \left[ D \right] \) is the elastic matrix. \( \left\{ \bar{F} \right\}^e \) is node load, including distributed load. \( \left[ B \right] \) is the strain matrix. \( \left[ \bar{K}_E \right]^e \) is the elastic stiffness matrix of the element. \( \left[ \bar{K}_\sigma \right]^e \) is the geometric stiffness matrix of the element. \( \left[ \bar{K}_\omega \right]^e \) is the stiffness matrix of the centrifugal softening of the element.

The load on the joint of a space beam element can be divided into two parts [10]: the first part is the external force acting directly on the element node, note as \( P_d \); the second part is the concentrated load, distributed load and so on. For uniform load (such as gravity, buoyancy and friction), the load of the whole element can be calculated one element at a time, and then distributed evenly on two nodes. These non-node loads should be converted to equivalent node loads, note as \( P_c \). The joint loads of these two parts are combined, that is, node loads on the element. Therefore, the total joint load of the external force:

\[
P = P_d + P_c
\]  

(7)

3. Simulation method

According to the hypothesis, drawing the rod-tube model in the Geometry module of Ansys Workbench, the five parts are synthesized by Boolean function. The model of rod-tube is generated finally. In the model system, the rod string and tubing are two separate entities. The force exerted on the sucker rod string in the tubing will induce deformation. It will contact the in wall of tubing under certain conditions. The nonlinear contact problem is solved by the augmented Lagrange equation. After the model is completed, the entire model is meshed. The model of sucker rod and tubing is divided into different meshes. The model of the rod string is a cylindrical entity. Dividing the grid is very uneven by regarding it as a solid. It is not conducive to the convergence of calculation results. It also affects the authenticity of simulation results seriously. In order to improve the grid quality, the model has been divided into five different entities at the same time. The five solid parts constitute the entire solid model, and then the whole sucker rod model is divided by global grids to generate uniform grid distribution. The in wall of the tubing is in friction with the rod string. Therefore, the grid quality is related to the simulation results. In order to make the mesh as uniform as the mesh of the sucker rod string, and the Mapped Face Meshing of the tubing was selected to generate the same uniform distribution grid as the sucker rod. In order to simulate the force of the pipe during normal operation, it is necessary to apply load to the rod string model and then simulate it. According to the hypothesis, the outer wall of the tubing is fixed to the outside during production. Therefore, the Cylindrical Support outside surface is applied at the tubing model. In actual production, the sucker rod string moves back and forth in its axial direction, so it is subjected to axial force. Therefore, the Polish rod load is applied at the upper end of the sucker rod string model. When the rod is working and the phenomenon of eccentric wear occurs in the radial direction of the rod string. The occurrence of radial buckling is a necessary condition to produce eccentric wear of the rod-tube. Simulation of maximum critical load of rod string buckling is carried out in this simulation. Pressure is applied on one side of the rod string. The overall analysis flow chart is shown in figure 3.
4. Simulation result and analysis

Simulation Basic Parameters: Steel rod elastic modulus $E=2\times10^{11}$ pa. $\rho=7850$ kg/m$^3$. The tubing diameter is 73mm. The inside diameter is 65mm. The diameter of rod string: $\varphi16$, $\varphi19$, $\varphi22$, $\varphi25$. The value range of polished rod load is 10-100kN. Based on the basic parameters of the simulation, the influence of rod diameter and polished rod load on the flexural contact stress of rod string is simulated. The simulation results are shown in figure 4. With figure 4, the radial variation of the stress of the rod string is affected by its diameter. As its diameter increases, the maximum stress becomes smaller, and it's a downward trend. The minimum stress is getting smaller and smaller, and it's also a downward trend. The radial variation of the stress of the sucker rod string is also affected by the variation of polished rod load. With the increase of polished rod load, the maximum stress increases, and shows an upward trend. The minimum stress also increases and tends to increase. Under varying diameters and polished rod load, the two maximum stress curves will intersect at one point. The two maximum stress line graphs divide the coordinate system into four parts. The left side is the selection of the optimal diameter and polished rod load.
5. Conclusion
Considering the influence of the buckling of the rod string in the tube, a simulation method of the buckling critical contact load of the rod string in the tube is established. In the detail, the finite element analysis dynamic model of sucker rod string is established by using double coordinate system. Ansys software is used to establish the simulation method of the contact load of the rod string buckling in the tube. The effects of material, diameter, polished rod load and radial load on the buckling critical contact load of the rod string are simulated and analyzed. Simulation results show that: The maximum stress decreases as the diameter of the rod string increases. The maximum stress of the rod string increases with increasing the polished rod load. The effect of polished rod load and rod diameter on buckling stress is considered comprehensively, and the optimum design area of the rod string is given. The simulation results have important theoretical and practical for optimal design of sucker rod pumping system and reasonable evaluation of oil well pump testing period.

Acknowledgments
This research was financially supported by Natural Science Foundation of Shandong Province (Grant NO. ZR2017LEE002 and ZR2016HB59), Scientific Research Starting Foundation of Linyi University (Grant NO. LYDX2016BS032), and Innovation and Entrepreneurship Foundation (Grant NO. 201710452066).

References
[1] Bastos, IC, Mayr, L. (2017) Development of Sensors Systems for the Validation of Mathematical Models for Sucker Rod Pumps. C. Society of Petroleum Engineers, SPE-185564-MS.
[2] Liu, C. (2009) Study on the mechanism of eccentric wear of sucker rod and its countermeasures. D. China university of petroleum..
[3] Xing, M. (2016) Response analysis of longitudinal vibration of sucker rod string considering buckling. J. Advances in Engineering Software. Commun. 99:49-58.
[4] Nickens H, Lea JF, Cox JC, Bhagavatula R, Garg D. (2005) Downhole beam pump operation: Slippage and buckling forces transmitted to the rod string. J. Journal of Canadian Petroleum Technology. Commun., 44(5): 05-05-05 PETSOC.
[5] Li, Z. (1999) Fundamental Equations And Its Applications For Dynamical Analysis Of Rod And Pipe String In Oil And Gas Wells. J. Acta Petrolei Sinica. Commun., 20(3):87-90.
[6] Chai, G. (2012) Study on eccentric wear mechanics of shaft pipe of lead vertical pumping element. D. Yanshan university.
[7] Huang, W., Gao, D., Liu, F. (2015) Buckling analysis of tubular string in horizontal wells. J. SPE Journal. Commun., 20:405-416.
[8] Gao, G., Miska S Z. (2008) Effects of Boundary Conditions and Friction on Static Buckling of Pipe in a Horizontal Well. IADC/SPE Drilling Conference, 4-6 March, Orlando, Florida, USA. Commun., 14:782-796.
[9] Han, H., Guo, L., Song, Y. (2003) Influence of resistance in polymer extract on eccentric wear of sucker rod tube. J. Journal of Daqing petroleum institute. Commun., (04): 21-23+38-118.

[10] Dong, S., Zhang, W., Wang, Q., Chai, G., Su, Y. (2012) Mechanism of eccentric wear of oil sucker rod pipe of direct well surface driven screw pump. J. Journal of petroleum. Commun., 33(02): 304-309.

[11] Chang, Y., Cong, Z. (2008) Causes of deviation and preventive measures of oil sucker rod in the well of gathering and driving direction. J. Journal of Daqing petroleum institute. Commun (01): 45-47+120.

[12] Zhang, W. (2011) Simulation study on mechanical characteristics of rod string of ground-driven screw pump. D. Yanshan university.