

Design of Titanium Alloy Mixed Sucker Rods Using API Recommendation Method

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Abstract: Titanium alloy, as a new type of material, has many advantages compared to ordinary metal materials: high specific strength, excellent toughness and fatigue resistance, excellent corrosion resistance, etc. Firstly, the wave equation of titanium alloy pumping rods was established. Then, the equivalent stiffness, equivalent bulk density, and equivalent elastic modulus of titanium alloy mixed pumping rods were derived, and the frequency coefficients of different rod column combinations were calculated. Finally, based on the above research, the steps for designing titanium alloy pumping rods using API recommendation method were summarized. Based on this, the design of titanium alloy pumping rods can be completed using API recommendation method through the above formulas and steps.

Keywords: Titanium alloy; Wave equation; API RP 11L Recommended Practice.

1. Introduction

With the continuous exploitation of petroleum resources, major oil fields in China have entered the mid to late stage of development. The dynamic liquid level has gradually decreased, the formation energy has decreased, and the extracted crude oil has gradually shifted to low-permeability oil layers. The pump hanging depth of mechanical extraction wells is increasing, which has brought a series of problems: the hanging point load of the pumping unit on the well has increased sharply, and the existing combination of rod pumps is unable to adapt to changes in well depth, Reduce the efficiency of the pumping system and increase energy consumption. [2]

Titanium alloy has many advantages required for deep well pumping, such as high strength and low density, which is more than 40% lighter than commonly used rod steel. This will help reduce the load on the pumping unit and reduce energy consumption; Titanium alloy can generate a dense oxide film in natural environments, which has good corrosion resistance and protection, and can adapt to acidic oil and gas field environments containing H₂S, CO₂, etc; It can still maintain good performance in high-temperature environments and is suitable for the extraction of some high-temperature oil reservoirs.

2. Longitudinal Vibration Model of Titanium Alloy Pumping Rod

In order to save costs and reduce the bending stress on the titanium alloy pumping rod string during the down stroke, and to reduce early fracture accidents of the pumping rod, a certain length of weighted rod is installed at the bottom of the titanium alloy pumping rod. When studying the longitudinal vibration characteristics of this titanium alloy mixed sucker rod string combination structure, a mechanical model as shown in Figure 1 can be used. This model can be described as a long variable diameter, variable rod material straight rod B that is fixed on foundation A and subjected to a concentrated external force F(t) at the bottom is forced to vibrate longitudinally, and there is a viscous damping force acting along the length of the rod, and foundation A has a

certain motion law.

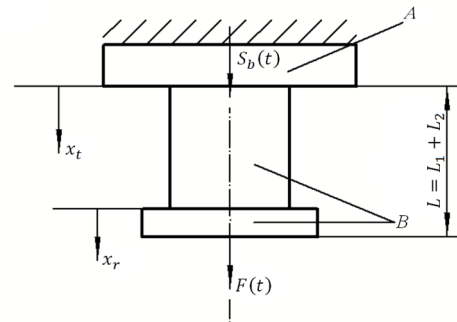


Figure 1. Mechanical model of titanium alloy mixed rod column

In the figure, $S_b(t)$ - the displacement of foundation A (donkey head suspension point) relative to the lower starting point at any time t , m.

Through the analysis of the physical balance of the unit in Figure 1, the mathematical model for the longitudinal undamped free vibration of the titanium alloy pumping rod column can be obtained as (without considering the weight of the rod column):

$$\frac{\partial^2 s_t(x_t, t)}{\partial t^2} - c_t^2 \frac{\partial^2 s_t(x_t, t)}{\partial x_t^2} = 0 \quad (1)$$

$$\frac{\partial^2 s_r(x_r, t)}{\partial t^2} - c_r^2 \frac{\partial^2 s_r(x_r, t)}{\partial x_r^2} = 0 \quad (2)$$

The boundary conditions are:

$$s_c(0, t) = 0.0 \quad (3)$$

$$E_r A_r \frac{\partial s_r(L_r, t)}{\partial x_r} = F(t) \quad (4)$$

The continuous condition are:

$$s_t(L_t, t) = s_r(0, t) \quad (5)$$

$$E_t A_t \frac{\partial s_c(L_t, t)}{\partial x_c} = E_r A_r \frac{\partial s_r(0, t)}{\partial x_r} \quad (6)$$

In the formula, $s(x, t)$ - the displacement of any section x in the titanium alloy pumping rod column relative to the foundation A (donkey head suspension point) at time t , m;

t - time, s;

E_t 、 E_r - elastic modulus of titanium alloy pumping rods and weighting rods, Pa;

A_t 、 A_r - cross-sectional area of titanium alloy pumping rods and weighting rods, m²;

L_c 、 L_r - The length of titanium alloy pumping rods and weighting rods, m.

3. Design Titanium Alloy Pumping Rods According to The Recommended Practice of API RP 11L

At present, there is no report on the use of titanium alloy as a material for the design of pumping rods at home and abroad, and the three widely used pumping rod design methods in the oil extraction engineering community are only applicable to conventional steel pumping rods. The first method is the empirical or semi empirical design method[3], which has been continuously improved since the birth of the rod pumping system. Most of it comes from rod manufacturers. The empirical or semi empirical design method has the characteristics of simplicity and practicality, but lacks theoretical basis; The second method is designed based on the results of solving the wave equation and related boundary conditions of the pumping rod string[4]. This method has the advantages of strong theoretical validity and high accuracy, and has been applied globally; The third method is the API method[5], which has a certain theoretical foundation, is safe, reliable, and convenient to use, and has been widely recognized by the international petroleum engineering community. This design method has been applied in tens of thousands of oil wells worldwide. However, its design criteria are based on some simplified conditions. Domestic and foreign scholars have proposed using the recommended method of API RP 11L to design fiberglass hybrid pumping rods [6], steel wire rope continuous pumping rods [7], and carbon fiber pumping rods[8]. By analogy with the above research, this article proposes to use the API RP 11L recommended method to design titanium alloy pumping rod columns, establish a longitudinal vibration system model of titanium alloy pumping rod columns, attempt to use the API recommended method to design titanium alloy pumping rod columns, calculate the equivalent elastic modulus, equivalent bulk density, equivalent stiffness, and natural frequency, and estimate the frequency coefficient of titanium alloy pumping rod combinations at different length ratios.

3.1. Equivalent elastic modulus

By treating the mixed rod column as a series spring, the equivalent elastic modulus of the series spring corresponding to the titanium alloy pumping rod column can be obtained according to the definition:

$$E_{tr} = \frac{1}{(A_r R_r + A_t R_t) \left(\frac{R_r}{A_r E_r} + \frac{R_t}{A_t E_t} \right)} \quad (7)$$

In this formula, E_{tr} - elastic modulus of titanium alloy rod column, Pa; R_r 、 R_t - the ratio of the length of the weighting

rod L_r and the length of the titanium alloy pumping rod L_t to the total length L of the rod, respectively.

3.2. Equivalent bulk density

According to the definition, the bulk density of titanium alloy pumping rods can be expressed as:

$$\rho_{tr} = \frac{\rho_r A_r R_r + \rho_t A_t R_t}{A_r R_r + A_t R_t} \quad (8)$$

So the propagation speed (m/s) of sound waves in titanium alloy pumping rods is:

$$c_{tr} = \sqrt{E_{tr} / \rho_{tr}} \quad (9)$$

3.3. Equivalent stiffness

According to the theory of elasticity, the equivalent elastic stiffness K_{tr} (N/m) of a titanium alloy pumping rod considered as a series spring is:

$$\frac{1}{K_{tr}} = \frac{R_t}{E_t A_t} + \frac{R_r}{E_r A_r} \quad (10)$$

3.4. Pole frequency coefficient

According to the vibration theory [9], the frequency equation for the longitudinal vibration of titanium alloy pumping rods can be obtained as follows:

$$1 - \frac{A_r E_r c_t}{A_t E_t c_r} \tan \frac{\omega}{c_t} R_t \tan \frac{\omega}{c_r} R_r = 0 \quad (11)$$

let

$$\frac{\omega}{c_i} R_i = \frac{\pi c_g}{2 c_i} R_{tr} R_i \quad (12)$$

In this formula, R_{tr} - The frequency coefficient represents the ratio of the natural frequency ω (rad/s) of a titanium alloy pumping rod to the natural fundamental frequency ω_g (rad/s) of a single stage steel rod of the same length.

Can be obtained:

$$\frac{A_r E_r c_t}{A_t E_t c_r} \tan \left(\frac{\pi c_g}{2 c_t} R_{tr} R_t \right) \times \tan \left(\frac{\pi c_g}{2 c_r} R_{tr} R_r \right) = 1 \quad (13)$$

In this formula, $c_t = (E_t / \rho_t)^{1/2}$ - The propagation speed of sound waves along titanium alloy pumping rods;

$c_r = (E_r / \rho_r)^{1/2}$ - The propagation speed of sound waves along the weighting rod;

$c_g = (E_r / \rho_r)^{1/2}$ - The propagation speed of sound waves along a single stage weighted rod of the same total length.

By using the trial and error method to solve R_{tr} , the natural frequency of titanium alloy pumping rods can be obtained:

$$\omega = R_{tr} \omega_g \quad (14)$$

4. Design Steps for Titanium Alloy Sucker Rod String

Referring to the API recommendation method for designing steel pumping rods, three different diameters of

titanium alloy rods and weighting rods were selected, as shown in Table 1. It is worth noting that titanium alloy has the characteristic of smaller elastic modulus compared to steel, which may cause overstroke effects in actual use of the pumping rod column. Therefore, attention must be paid in design to minimize the frequency coefficient of the mixed rod column, so as to maximize the factor of 1, S_p/S .

In terms of material selection, this article selected Ti-6Al-4V titanium alloy material, which belongs to ($\alpha+\beta$) Type titanium alloy, combining the advantages of two types of titanium alloy materials, which are good plasticity, good thermal strength (can work at 400 °C for a long time), strong resistance to seawater corrosion, and good comprehensive mechanical properties.

Table 1. Mechanical parameters of titanium alloy mixed sucker rods

Code	Rod Diameter d/mm	Linear Density $\rho_l/\text{kg} \cdot \text{m}^{-1}$	Elastic Modulus E/ 10^5MPa
titanium alloy	1	19	1.28
	2	22	1.71
	3	25	2.21
sinker bar	1'	22	3.19
	2'	25	4.12
	3'	29	5.54

Table 2. Characteristic parameters of rods and columns

Pole column combination	Titanium alloy sucker rod length ratio/%	wave velocity $c_{tr}/(\text{m} \cdot \text{s}^{-1})$	Elastic modulus $E_{tr}/(10^5\text{MPa})$	bulk density $\rho_{tr}/(\text{kg} \cdot \text{m}^{-3})$	frequency coefficient	Pole column combination	Titanium alloy sucker rod length ratio/%	wave velocity $c_{tr}/(\text{m} \cdot \text{s}^{-1})$	Elastic modulus $E_{tr}/(10^5\text{MPa})$	bulk density $\rho_{tr}/(\text{kg} \cdot \text{m}^{-3})$	frequency coefficient
1-1'	10	4797.5	1.8641	8099.2..	0.7392	2-2'	60	4528.4	1.2925	6303.0	0.6156
1-1'	20	4654.3	1.6864	7784.9	0.6696	2-2'	70	4572.4	1.2311	5888.5	0.6361
1-1'	30	4558.3	1.5487	7453.4	0.6287	2-2'	80	4652.0	1.1797	5451.2	0.6749
1-1'	40	4501.9	1.4396	7103.1	0.6070	2-2'	90	4772.6	1.1364	4989.0	0.7401
1-1'	50	4480.8	1.3517	6732.4	0.6000	2-3'	10	4.670.3	1.7805	8163.2	0.6977
1-1'	60	4493.4	1.2800	6339.5	0.6064	2-3'	20	4453.2	1.5681	7907.2	0.6150
1-1'	70	4541.0	1.2212	5922.2	0.6273	2-3'	30	4314.4	1.4196	7626.4	0.5697
1-1'	80	4626.6	1.1727	5478.4	0.6671	2-3'	40	4235.7	1.3127	7316.7	0.5466
1-1'	90	4757.3	1.1328	5005.3	0.7344	2-3'	50	4208.2	1.2350	6973.8	0.5393
1-2'	10	4672.3	1.7819	8162.4	0.6983	2-3'	60	4228.8	1.1788	6591.7	0.5461
1-2'	20	4456.4	1.5700	7905.7	0.6157	2-3'	70	4299.7	1.1395	6163.6	0.5687
1-2'	30	4318.1	1.4216	7624.1	0.5705	2-3'	80	4429.1	1.1143	5680.3	0.6130
1-2'	40	4239.7	1.3147	7313.9	0.5473	2-3'	90	4633.2	1.1014	5130.7	0.6938
1-2'	50	4212.3	1.2368	6970.5	0.5401	3-1'	10	4962.3	1.9474	7908.4	0.8119
1-2'	60	4232.7	1.1803	6588.2	0.5469	3-1'	20	4931.7	1.8111	7446.3	0.7801
1-2'	70	4303.4	1.1408	6160.1	0.5695	3-1'	30	4908.7	1.6888	7008.9	0.7577
1-2'	80	4432.1	1.1152	5677.3	0.6136	3-1'	40	4892.9	1.5787	6594.4	0.7445
1-2'	90	4635.1	1.1019	5128.8	0.6943	3-1'	50	4884.1	1.4792	6201.0	0.7398
1-3'	10	4488.7	1.6562	8220.0	0.6464	3-1'	60	4882.2	1.3889	5827.0	0.7433
1-3'	20	4182.8	1.4031	8019.7	0.5534	3-1'	70	4887.0	1.3067	5471.2	0.7752
1-3'	30	3998.2	1.2456	7791.9	0.5061	3-1'	80	4898.9	1.2317	5132.2	0.7759
1-3'	40	3897.5	1.1439	7530.3	0.4827	3-1'	90	4917.8	1.1630	4808.8	0.8055
1-3'	50	3863.8	1.0789	7226.9	0.4755	3-2'	10	4903.0	1.9250	8007.7	0.7808
1-3'	60	3892.0	1.0408	6870.9	0.4834	3-2'	20	4829.6	1.7769	7618.0	0.7301
1-3'	70	3986.5	1.0246	6447.2	0.5054	3-2'	30	4777.8	1.6500	7228.2	0.6976
1-3'	80	4162.8	1.0284	5934.5	0.5519	3-2'	40	4745.5	1.5400	6838.5	0.6793
1-3'	90	4455.7	1.0525	5301.4	0.6433	3-2'	50	4731.7	1.4438	6448.7	0.6732
2-1'	10	4903.0	1.9250	8007.7	0.7808	3-2'	60	4735.6	1.3588	6059.0	0.6783
2-1'	20	4829.5	1.7769	7618.3	0.7302	3-2'	70	4757.8	1.2833	5669.2	0.6956
2-1'	30	4777.8	1.6500	7228.2	0.6976	3-2'	80	4798.8	1.2158	5279.5	0.7268
2-1'	40	4745.5	1.5400	6838.5	0.6793	3-2'	90	4860.2	1.1550	4889.7	0.7751
2-1'	50	4731.7	1.4438	6448.7	0.6732	3-3'	10	4795.9	1.8631	8100.2	0.7387
2-1'	60	4735.6	1.3588	6059.0	0.6785	3-3'	20	4651.8	1.6850	7786.8	0.6690
2-1'	70	4757.8	1.2833	5669.2	0.6957	3-3'	30	4555.2	1.5471	7456.0	0.6280
2-1'	80	4798.8	1.2158	5279.5	0.7268	3-3'	40	4498.4	1.4380	7106.2	0.6063
2-1'	90	4860.2	1.1550	4889.7	0.7751	3-3'	50	4477.1	1.3502	6735.9	0.5993
2-2'	10	4813.2	1.8739	8088.7	0.7449	3-3'	60	4490.1	1.2788	6343.0	0.6057
2-2'	20	4680.0	1.7008	7765.3	0.6776	3-3'	70	4537.9	1.2202	5925.5	0.6267
2-2'	30	4590.2	1.5647	7426.3	0.6375	3-3'	80	4624.1	1.1720	5481.1	0.6665
2-2'	40	4536.8	1.4553	7070.4	0.6161	3-3'	90	4755.7	1.1324	5006.9	0.7340
2-2'	50	4516.7	1.3661	6696.5	0.6093						

From Table 2, it can be seen that when the ratio of titanium alloy rods to weighting rods is close, the frequency coefficient of the hybrid rods is the smallest. However, under the condition of a constant rod length ratio, when titanium alloy rods with the same diameter are matched with weighting rods with larger diameters, the frequency coefficient of the hybrid rods is also smaller. When selecting the diameter of the lower weighting rod, consideration should be given to the frequency coefficient and additional load.

The steps for designing titanium alloy pumping rod columns using the API RP 11L recommendation method are:

(1) Preliminary selection of diameter specifications and length ratios for titanium alloy pumping rods and weighting

rods;

(2) Calculate the equivalent elastic modulus E_{tr} and equivalent bulk density of titanium alloy pumping rod combinations ρ_{TR} , equivalent stiffness K_{tr} , and natural frequency of vibration ω ;

(3) Design parameters for dimensionless factor relationship curves according to API RP 11L recommended practice;

(4) Verify the strength of the titanium alloy pumping rod string.

The design should be carried out using the recommended method of API RP 11L, and the trial and error method should be used repeatedly until the design results meet the user's requirements.

5. Conclusion

Due to the fact that the elastic modulus of titanium alloy material is only 47.6% -57.1% of that of steel material, in practical use, the mixed rod column can form an overtravel of the pump plunger, increasing oil well production. The superior physical properties of titanium alloy also indicate its application prospects in deep well pumping systems. This article provides the steps for designing titanium alloy pumping rods using API recommendation method, calculates the equivalent bulk density, equivalent stiffness, equivalent elastic modulus and other parameters of titanium alloy hybrid rods, and uses trial algorithms to calculate the natural frequencies of different rod column combinations. It is hoped that this will provide assistance for the design of titanium alloy pumping rods in the future.

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