

# Vibration Control of Reinjection Pump Room Pipeline System Based on Dynamic Characteristic Analysis

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## Abstract

The reinjection pump room plays a crucial role in industries such as petroleum and chemical engineering. Its main responsibility is to safely and effectively inject treated wastewater, exhaust gas, or other fluid substances into the formation, aiming to achieve resource recycling and environmental protection. However, the pipeline system of the reinjection pump room usually has complex spatial distribution, long span, and multi-point elastic support characteristics, which may cause structural vibration during operation, and have adverse effects on the stable operation, safety, and surrounding environment of the equipment. Therefore, in the pipeline design stage, it is crucial to conduct in-depth vibration analysis of complex pipeline systems to ensure that harmful resonance phenomena do not occur in the pipeline under working conditions. Given the potential impact of pipeline system vibration on equipment performance and surrounding environment, effective suppression of pipeline system structural vibration is of great practical significance. This article focuses on the vibration control strategy of the reinjection pump room pipeline system based on dynamic characteristic analysis. By conducting in-depth research on the dynamic characteristics of pipeline systems, including vibration frequency, modal analysis, and vibration transmission paths, the aim is to propose a set of targeted vibration control measures.

## Keywords

Dynamic Characteristic Analysis; Reinjection Pump Room Pipeline System; Vibration Control.

## 1. Introduction

As an indispensable and important facility in industrial production, the reinjection pump room carries the key task of safely injecting treated wastewater, exhaust gas, or other fluid substances into the formation [1]. This process not only contributes to the recycling of resources, but also effectively protects the environment and reduces the emission of pollutants [2]. However, the normal operation of the reinjection pump room involves numerous complex engineering problems, among which the vibration control of the pipeline system is particularly crucial. As a core component of the reinjection pump room, the stability and reliability of the pipeline system are directly related to the safe operation of the entire facility [3]. However, due to the complex spatial distribution, long span, and multi-point elastic support of pipeline systems, they are easily affected by various factors during operation, resulting in structural vibration. This kind of vibration not only causes damage to the equipment, reduces its service life, but may also cause noise pollution to the surrounding environment, affecting people's normal life and work [4].

The fluid inside the pipeline is affected by various factors such as pressure changes, pipeline bends, and pipe diameter changes during the flow process, resulting in changes in flow velocity [5]. This change in flow rate further triggers vibration of the pipeline structure. In some cases, resonance occurs when the natural frequency of the pipeline system is close to or equal to the

external excitation frequency [6]. In resonance state, the pipeline system will generate significant vibration, leading to a decrease in support stiffness or detachment of connection joints [7]. More seriously, high vibration stress may even lead to cracks or even fractures in pipeline systems, posing serious safety hazards to industrial production. Therefore, analyzing the dynamic characteristics of complex pipeline systems and obtaining their dynamic characteristics becomes the key to solving vibration problems in pipeline systems. In addition, the vibration and noise of pipeline systems are also an issue that cannot be ignored. Vibration noise is mainly generated by the vibration of the vibration source equipment and fluid excitation in the pipeline. Both types of excitation sources can cause resonance in the pipeline and its supporting structure, resulting in strong noise pollution.

Long term exposure to high noise environments not only poses a threat to the physical and mental health of operators, but may also affect the quality of life of surrounding residents. Therefore, the control of vibration and noise in pipeline systems is also of great significance. By analyzing the dynamic characteristics of the pipeline system and formulating targeted vibration control measures, the safety and reliability of the reinjection pump room can be effectively improved, making a positive contribution to the sustainable development of industrial production and environmental protection. With the continuous development and innovation of industrial technology, the vibration control technology of the pipeline system in the reinjection pump room will also be continuously improved and perfected. By introducing advanced sensors, control systems, and intelligent algorithms, real-time monitoring and intelligent regulation of the vibration status of pipeline systems can be achieved, further improving their operational efficiency and stability.

## 2. The Hazards and Causes of Pipeline Vibration

Pipeline vibration is a common problem during the operation of the reinjection pump room, which not only has a negative impact on equipment performance, but may also lead to safety hazards and environmental pollution [8]. A deep understanding of the hazards and causes of pipeline vibration is of great significance for ensuring the safe, stable, and efficient operation of the reinjection pump room [9]. Firstly, pipeline vibration can cause additional loads on the mechanical connection components of the pipeline and water pump, causing damage to them [10]. In the case of resonance, this kind of damage is particularly severe, which may lead to component bending, bending, and even fracture, seriously affecting the normal operation of the equipment. Secondly, pipeline vibration can cause fluctuations in the data collected during testing, thereby reducing the accuracy of the testing system. This is an issue that cannot be ignored for scenarios that require precise measurement of fluid parameters or equipment performance. And pipeline vibration can seriously affect the stability of the testing system, making it difficult for the equipment to maintain long-term, continuous, and stable operation. This not only affects production efficiency, but may also increase maintenance costs and downtime. Finally, pipeline vibration can generate noise, affecting the water pump testing environment and posing a threat to the physical and mental health of operators. Meanwhile, noise may also interfere with the normal operation of other equipment, affecting the stability of the entire production line.

The reasons for pipeline vibration are as follows. Firstly, cavitation of the water pump itself is an important cause of pipeline vibration. Cavitation can cause the formation of bubbles in the fluid, which will aggregate and rupture during the flow process, generating impact force and causing pipeline vibration. In addition, the throttling effect formed by the high-speed fluid flowing through the electromagnetic gate valve in the pipeline will also generate a pressure difference. When the pressure difference reaches a certain value, it will also cause pipeline vibration. Secondly, if the flange of the pipeline connection is not tightened or the tightness of

the surrounding screws is uneven, it will cause vibration in the pipeline. In addition, if the horizontal levelness of the bearing connection is not adjusted properly, it can also cause vibration in the water pump pipeline. These installation and debugging issues are often caused by improper operation or negligence. Finally, unreasonable pipeline design, such as excessive changes in pipe diameter and excessive bends, can lead to unstable phenomena such as eddy currents and turbulence during fluid flow, resulting in pipeline vibration. In addition, the unreasonable design of pipeline support structures may also lead to pipeline vibration.

### 3. Analysis of Dynamic Characteristics of Pipeline Vibration

#### 3.1. Vibration Control Algorithm

For pipeline systems, the suppression of vibration and noise is a complex and critical engineering problem. Although the most direct and effective method is to suppress the vibration source of the pipeline, that is, to eliminate the excitation force, in practical applications, completely eliminating the vibration source is often costly and even difficult to achieve for pipeline systems that have already been put into use. Therefore, other practical and feasible measures need to be taken to suppress the vibration of the pipeline and control the vibration response within an acceptable range. The differential equation for the structural motion of pipeline systems can be expressed as:

$$\begin{cases} M\ddot{X} + C\dot{X} + KX = F(t) \\ X(t_0) = X_0 \\ \dot{X}(t_0) = \dot{X}_0 \end{cases} \quad (1)$$

In the formula,  $M, C, K \in R^{n \times n}$  represents the mass matrix, damping matrix, and stiffness matrix of the pipeline structure;  $X(t) \in R^n$  is the displacement vector of the pipeline structure;  $\ddot{X}(t) \in R^n, \dot{X}(t) \in R^n$  is the vibration acceleration and vibration velocity of the pipeline structure particles;  $X(t_0), \dot{X}(t_0) \in R^n$  is the initial displacement vector and initial velocity vector of the pipeline structure;  $F(t)$  is the vector of excitation forces acting on the pipeline structure, which includes mechanical vibration, fluid vibration, and seismic excitation forces.

If there are prominent stable line spectrum characteristics in the vibration signal of the pipeline system, it means that the vibration signal has a clear and stable frequency component in the frequency domain. To effectively suppress these line spectrum vibrations, it is first necessary to generate a reference signal. This reference signal is usually generated by the controller, and its frequency matches the angular frequency of the line spectrum vibration that needs to be controlled. The frequency of the expected signal is an important parameter for system operation. By estimating the angular frequency parameters  $\{\omega_k\}_{k=1}^K$  of the line spectrum vibration that needs to be controlled, where  $K$  is the number of frequencies. Considering offline identification of secondary channels, at each frequency  $\omega_k (k=1, \dots, K)$ , we calculate the

corresponding secondary channel response  $\hat{S}_{ijk} = \frac{E_{jk}}{Y_{ik}} (i=1, \dots, I; j=1, \dots, J; k=1, \dots, K)$  based on the signal  $E_{jk} (j=1, \dots, J)$  from each secondary source  $Y_{ik} (i=1, \dots, I)$  to each error sensor. After obtaining the line spectrum frequency parameters and estimating the secondary channels, the algorithm using the following formula is used to perform multi-channel adaptive control on the source signal.

$$\tilde{x}_{ijk}(n) = \hat{S}_{ijk} x_k(n) \quad (2)$$

$$w_{ik}(n) = w_{ik}(n-1) - \mu \sum_{j=1}^J \tilde{x}_{ijk}^*(n) e_j(n) \tag{3}$$

$$y_i(n) = \sum_{k=1}^K w_{ik}^*(n) x_k(n) \tag{4}$$

### 3.2. Experimental Result

To verify the effectiveness of the strategy proposed in this article in vibration control of pipeline systems, targeted experiments were conducted, and the vibration response of pipeline systems before and after using the strategy was estimated and compared. Table 1 shows the estimated results of the vibration response of the pipeline system before and after using the strategy proposed in this paper. From the table, it can be seen that the vibration response of the pipeline outlet optimized by the strategy has significantly decreased near the two key frequency points of 80Hz and 300Hz. This result fully demonstrates the effectiveness of the proposed strategy in suppressing pipeline system vibration. The vibration control strategy proposed in this article has significant effectiveness in vibration control of pipeline systems. It can effectively reduce the vibration response of pipeline outlets, improve the stability and reliability of the system, and provide strong guarantees for the normal operation of industrial production.

**Table 1.** Estimated results of vibration response ( $m \cdot s^{-2}$ )

Frequency/Hz	Vibration response amplitude	
	Before optimization	After optimization
80	0.78	0.16
200	0.59	0.28
300	0.43	0.21

**Table 2.** Comparison of flow rates at the same point before and after pipeline renovation

$m^3 / h$

Number	Before renovation	After renovation
1	460.3	450.5
2	463.9	451.2
3	455.6	450.7
4	450.9	449.3
5	453.8	448.7

Table 2 provides a detailed comparison of flow rates at the same point before and after pipeline renovation. From these data, several important changes can be observed. Firstly, after the pipeline renovation, the tested flow values remained within the normal range with minimal fluctuations. This indicates that the renovated pipeline system can stably transport fluids with little change in flow rate, which is conducive to ensuring the continuity and stability of the production process. Secondly, pipeline vibration is greatly reduced. This is a significant achievement achieved after the implementation of the strategy in this article. The reduction of vibration not only prolongs the service life of pipelines and equipment, reduces maintenance costs, but also improves the safety of the production environment and reduces the health risks that operators may face due to prolonged exposure to vibration environments. In addition, the on-site noise has significantly decreased. This is also a positive effect brought about by pipeline renovation. The reduction of noise not only improves the working environment and enhances the comfort of operators, but also helps to reduce the impact of noise on the surrounding environment and residents, in line with the requirements of environmental protection and

sustainable development. In summary, the data in Table 2 fully demonstrates the effectiveness of our strategy in pipeline system renovation.

## 4. Conclusion

Reducing the vibration of the reinjection pump room pipeline system and ensuring the safe and stable operation of the pipeline is not only crucial for ensuring the continuity and stability of the production process, but also of great significance for reducing equipment damage, extending service life, and improving the quality of the working environment. Significant results have been achieved by implementing the vibration control strategy proposed in this article. Firstly, the vibration of the pipeline has been significantly reduced. This not only reduces the additional load and damage caused by vibration of the equipment, improves the stability and reliability of the system, but also lays a solid foundation for the long-term stable operation of the equipment. Secondly, the stability of traffic has been significantly improved. The renovated pipeline system has minimal flow fluctuations and remains within the normal range during operation. This is conducive to ensuring the continuity and stability of the production process, improving production efficiency and quality. Meanwhile, stable flow also helps to reduce equipment failures and safety hazards caused by flow fluctuations. In addition, the on-site noise has significantly decreased. Reducing pipeline vibration can effectively reduce the generation and propagation of noise. This not only improves the working environment, enhances the comfort and efficiency of operators, but also meets environmental requirements, reducing the impact of noise on the surrounding environment and residents. These improvements not only enhance the performance and reliability of equipment, but also create a safer, more comfortable, and environmentally friendly working environment for enterprises.

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