

## Design Methodology of Straight Fluid-Conveying Pipes in Nuclear Power Plants Under Stochastic Vibration

**Authors:** Lai, Mr. Chao, Qu, Prof. Wei, Peng, Ms. Tian-Lin, Liang, Yong-Fu, Xia, Prof. Liang-Shu, Qu, Prof. Wei

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### Abstract

Stochastic vibration in nuclear power plants can amplify the cyclic stress, vibratory displacement, and velocity response of straight fluid-conveying pipes in the primary loop. To address this issue, a stochastic-vibration mathematical model for clamped-clamped straight pipes under stochastic excitation is established. The model integrates stochastic vibration theory with the finite-element method, thereby systematically quantifying how pipe-support locations and structural parameters influence the natural frequencies and stochastic displacement, velocity, and stress responses of fluid-conveying straight pipes. Relocating the support along the span first increases and then decreases the natural frequency, with a peak occurring at node 8. Longer pipes reduce both natural frequency and stress but enlarge displacement and velocity amplitudes. A larger internal diameter suppresses displacement, velocity, and stress while raising the natural frequency. Thicker pipe walls attenuate displacement and velocity responses but increase stress and frequency. To optimize performance, we applied a multi-objective genetic algorithm to pipes with adjustable mid-span support under stochastic excitation. Compared to the baseline design, the Pareto-optimal solutions yield a maximum upshift of 28.98% in fundamental frequency, while the Root Mean-Square (RMS) displacement, velocity, and stress are curtailed by up to 24.83%, 24.54%, and 20.55%, respectively. These findings provide a quantitative benchmark for pipe sizing and vibration-mitigation strategies in future nuclear primary piping systems.

## Full Text

# Design Methodology of Straight Fluid-Conveying Pipes in Nuclear Power Plants Under Stochastic Vibration

Chao Lai<sup>1,3</sup>, Tian-lin Peng<sup>1,3</sup>, Yong-fu Liang<sup>1,3</sup>, Liang-shu Xia<sup>1,3\*</sup>, Wei Qu<sup>2,3\*</sup>

<sup>1</sup>College of Mechanical Engineering, University of South China, Hengyang 421001, China

<sup>2</sup>Key Laboratory of Advanced Nuclear Energy Design and Safety, Ministry of Education, Hengyang 421001, China

\*Corresponding authors. E-mail addresses: 563493574@qq.com (W. Qu), 2000000476@usc.edu.cn (L.S. Xia)

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## Abstract

Stochastic vibration in nuclear power plants can amplify cyclic stress, vibratory displacement, and velocity response of straight fluid-conveying pipes in the primary loop. To address this challenge, a stochastic-vibration mathematical model for clamped-clamped straight pipes under stochastic excitation is established by integrating stochastic vibration theory with the finite-element method. This model systematically quantifies how pipe-support locations and structural parameters influence natural frequencies and stochastic displacement, velocity, and stress responses of fluid-conveying straight pipes. Relocating the support along the span first increases and then decreases the natural frequency, with a peak observed at node 8. Longer pipes reduce both natural frequency and stress but enlarge displacement and velocity amplitudes. A larger internal diameter suppresses displacement, velocity, and stress while raising natural frequency. Thicker pipe walls attenuate displacement and velocity responses but increase stress and frequency. To optimize performance, a multi-objective genetic algorithm was applied to pipes with adjustable mid-span support under stochastic excitation. Compared to the baseline design, the Pareto-optimal solutions yield a maximum upshift of 28.98% in fundamental frequency, while the Root Mean-Square (RMS) displacement, velocity, and stress are curtailed by up to 24.83%, 24.54%, and 20.55%, respectively. These findings provide a quantitative benchmark for pipe sizing and vibration-mitigation strategies in future nuclear primary piping systems.

**Keywords:** Stochastic vibration; Nuclear power plant; Straight Fluid-Conveying Pipes; Design methodology

## 1. Introduction

Nuclear power plants frequently experience strong vibratory influences, with primary loop piping systems subjected to mechanical excitation from nuclear reactions and self-excited vibration of internal fluid flow. Under actual operating conditions, these vibrations exhibit stochastic characteristics. Piping systems constitute the most critical channels for transporting energy and media in nuclear power plants, and their performance directly impacts plant operational efficiency. Straight pipes, as the most common components in these systems, operate continuously under stochastic vibration conditions. Severe vibrations generate large cyclic stresses, displacements, and velocity responses, while fluid-structure interaction profoundly affects pipe vibration characteristics. These effects can lead to fatigue damage, loosening, wear, and leaks, posing serious threats to both piping system reliability and overall plant safety. Consequently, studying the vibration response of straight nuclear power transmission pipelines under stochastic excitation is essential for developing effective design methods to improve reliability and safety.

Regarding the vibration response of flow-conveying pipelines, Ding et al. [1] focused on vibration control technology, revealing that pipelines are susceptible to vibration induced by multiple factors including fluid self-excitation, support structures, and operating environments. Severe vibrations can generate variable dynamic stresses and significant deformations, ultimately leading to fatigue failure. Fan et al. [2] established the vibration equation for fluid-structure coupled flow pipelines based on Hamilton's principle and numerically analyzed how support stiffness and position affect frequency, modal functions, and critical flow velocity. Bozyigit et al. [3] conducted free vibration analysis under various boundary conditions using the differential transformation method and Adomian decomposition method, examining natural frequencies, vibration modes, and transient instability flow velocities under different support configurations. Huang et al. [4] employed the Galiot-Kim method to analyze natural frequency variation patterns in simply supported straight pipelines under different boundary conditions, with conclusions applicable to nuclear and other industrial pipelines.

Tan et al. [5-6] used the Timoshenko beam model to establish a fluid-structure interaction model and applied the Finite Element Method (FEM) to analyze how fluid and structural parameters affect pipeline stability and vibration response. Zhai et al. [7] employed FEM to establish Timoshenko dynamic equations for fluid-conveying pipelines, investigating fluid velocity effects on natural frequency and dynamic response standard deviation, while also calculating displacement and velocity responses [8]. Sazesh et al. analyzed cantilevered flow pipelines under distributed stochastic excitation, focusing on how response spectral density and variance change with flow velocity and discussing pipeline flutter speed and frequency.

Yamashita et al. [9-10] investigated self-excited vibrations in cantilevered flow

pipes with elastic supports and end masses, discovering hybrid modal self-excited vibrations caused by Hopf-Hopf interactions within specific parameter ranges. Abdelbaki et al. [11] established a mechanical-theory-based model for straight flow pipes and numerically analyzed how different support configurations, stiffness, and structural parameters influence vibration response. Qu et al. [12] investigated elbows in flow pipes with and without harmonic excitation, demonstrating how excitation and structural parameters affect vibration properties. For vibration mitigation, Tang et al. [13] reviewed recent advances in pipeline vibration and control, examining active and passive control technologies for various pipeline types while discussing emerging technologies like machine learning in pipeline control systems. Kwag et al. [14] designed tuned mass dampers for nuclear power plant pipelines under stochastic seismic loads, reducing maximum seismic acceleration, RMS acceleration, and spectral acceleration responses by 34%, 41%, and 57%, respectively. Pourmohammadi et al. [15] constructed a nonlinear energy absorber by attaching a sliding mass oscillator to flow pipelines, effectively preventing resonance across wide flow velocity and external excitation ranges. Farid et al. [16] applied Hamilton's principle to pipelines under moving loads and used a harmonic search algorithm to optimize displacement responses under varying load lengths, thicknesses, and flow velocities.

Tian et al. [17] proposed a design method to prevent pipeline resonance by adjusting fixed clamps, revealing that modifying clamp stiffness and position can effectively prevent natural frequencies from falling within mechanical operation frequency ranges. Xin et al. [18] employed the transfer matrix method to establish a mathematical model of a multi-pump pipeline and obtained optimal solutions using a chaotic swarm optimization algorithm, reducing pipeline vibration response by 36.4% compared to original fixture positions. Colombo et al. [19] simulated composite flow pipes under actual operational conditions, designing parameters such as wall thickness and winding angle to reduce fatigue damage. Dominik et al. [20] addressed strong lateral vibration in straight flow pipes at critical velocities by designing novel instability controllers, validated through numerical simulations. Zadkarami et al. [21] proposed a pipeline leak diagnosis method using big data-driven deep neural networks, achieving high accuracy by training real-time flow and pressure signals.

Regarding nuclear power plant piping systems, Ju et al. [22] investigated tuned mass damper effectiveness under various seismic load conditions by constructing a full-scale numerical model, evaluating their impact on seismic vulnerability curves. Mano et al. [23] addressed performance degradation in flow-carrying piping systems under seismic loads by employing flow rate as a numerical indicator to reflect deterioration levels. Sun et al. [24] developed a fluid-structure interaction mathematical model for hot water pipes in nuclear reactor insulation layers, analyzing temperature and stress influence patterns with experimental validation. Beal et al. [25] proposed a novel reliability analysis method coupling failure physics models with maintenance performance analysis for real-time pipeline condition monitoring. Oh et al. [26] developed a real-time unmeasured dynamic

response prediction method for nuclear power plant pressure pipes by measuring limited physical responses to predict inaccessible dynamic responses. Gao et al. [27] proposed a vibration reduction design method integrating BP-ANN with the NSGA-II algorithm for optimizing flow-carrying pipe dynamic responses in nuclear power plants, deriving optimal parameters to reduce vibration-induced failures with experimental validation. Tomarov et al. [28] investigated erosion-corrosion interaction characteristics between single-phase and two-phase fluids and metals, proposing a kinetic migration theory-based method to identify localized maximum erosion-corrosion thinning regions. Hak et al. [29] employed a virtual crack size distribution model to assess failure probability by analyzing crack depth distribution, crack density, and detection performance levels. Dacosta et al. [30] used large eddy simulation to analyze fluid flow at mixing points, developing a fatigue assessment detection method for welded joints and stress concentration zones. Cancemi et al. [31] established a finite element simulation model for nuclear pipelines, analyzing results using neural networks and ARIMA models to predict remaining service life. Zhao et al. [32] established an experimental leak detection platform for nuclear pipelines, identifying and locating faults by analyzing leak aperture and pressure effects on acoustic signal time-frequency characteristics. Chen et al. [33] proposed an online structural integrity assessment system for nuclear power plant main loop pipelines using thermoelectric potential and failure assessment mapping for real-time aging condition monitoring. Wu et al. [34] developed an online leak detection system based on machine learning-driven fracture angle diagnosis, establishing a comprehensive “early warning-localization-angle” monitoring framework. Allah et al. [35] reviewed machine learning and deep learning applications for corrosion and crack detection in nuclear power plant transport pipelines, highlighting their promise for enhancing detection accuracy and efficiency.

In summary, domestic and international research on flow pipelines has primarily focused on self-excited and harmonic-excited fluid flow, while nuclear pipeline studies have concentrated on materials, corrosion, leakage, fatigue, and performance monitoring. However, nuclear power pipelines typically operate in stochastic vibration environments, and little research has examined how support position changes affect vibration characteristics or optimized structural parameters for nuclear pipelines. This paper addresses this gap by analyzing how natural frequency, displacement, velocity, and stress vary in a straight nuclear pipeline with a fixed left end and movable fixed support under different structural parameters. The objective is to reduce pipeline displacement, velocity, and stress responses while increasing natural frequency, thereby proposing a design methodology that reflects actual operating conditions and prevents damage from design flaws.

## 2. Establishment and Solution of Straight Pipe Mathematical Models

### 2.1 Establishment of a Mathematical Model for Stochastic Vibration

Stochastic vibrations generated by nuclear reactions are transmitted to the pipeline through fixed supports. Based on the position of the movable fixed support at the left end, the pipeline is divided into ten equal sections where  $L_i$  denotes the support position, with  $i = 2, 3, 4, 5, 6, 7, 8, 9, 10, 11$ , as illustrated in Figure 1 [Figure 1: see original paper]. Stochastic vibration is transmitted to the pipeline through rigid supports.

A mathematical model for straight flow-carrying pipe vibration under stochastic excitation was established using stochastic vibration theory, bidirectional fluid-structure interaction theory, and the finite element method. The vibration equation is as follows:

where  $M$  represents the overall mass matrix of the pipeline,  $C$  denotes the overall damping matrix,  $K$  indicates the overall stiffness matrix,  $a$  refers to the displacement response vector,  $b$  is the stochastic vibration intensity vector indicating the location and intensity of excitation, and  $X_g$  represents the stochastic vibration acceleration.

Pipelines are typically analyzed using the Timoshenko beam model, in which the pipeline is treated as a thin-walled slender pipe while accounting for shear strain effects and moment of inertia. As illustrated in Figure 2 [Figure 2: see original paper],  $\alpha$  represents the lateral displacement of the beam element,  $\beta$  denotes the cross-sectional rotation angle, and  $\gamma$  indicates the longitudinal displacement of the beam element.

According to finite element assumptions, the displacement field of the straight pipe flow unit is expressed as follows:

Moreover, the strain energy of a straight pipe unit under stochastic vibration is denoted by:

As for the kinetic energy of a straight flow-conveying pipe unit under stochastic vibration, it is modeled as follows:

According to Hamilton's principle, we obtain:

In Eqs. (2) to (5),  $Z$  denotes the shape function matrix for longitudinal displacement of the pipeline,  $B$  represents the shape function matrix for lateral displacement,  $U$  indicates the shape function matrix for rotational displacement of the pipeline cross-section,  $a$  represents the vector of degrees of freedom at the nodes of the straight pipe element,  $L$  denotes the length of the beam element,  $E$  is the elastic modulus,  $I$  indicates the moment of inertia of the pipeline cross-section,  $A$  represents the cross-sectional area of the pipeline element,  $x$  is the longitudinal position coordinate,  $G$  is the shear modulus,  $\gamma$  denotes the shear coefficient,  $\gamma$  represents the shear strain,  $m_f$  is the mass per unit length of the

fluid element,  $v$  highlights the fluid velocity,  $P$  is the fluid pressure in the pipe,  $m_p$  is the mass per unit length of the pipe element,  $\rho_p$  denotes the volumetric mass of the pipe element,  $\rho_f$  is the volumetric mass of the fluid element,  $I_p$  represents the sectional moment of inertia of the pipe element, and  $I_f$  is the sectional moment of inertia of the fluid element.

This study assumes steady, incompressible fluid flow and accounts for bidirectional fluid-structure interaction between the pipeline and fluid. By substituting Eqs. (2), (3), and (4) into Eq. (5), the damping matrix, stiffness matrix, and mass matrix of the straight flow pipe element are obtained, respectively:

where  $[C]$  denotes the damping matrix of the straight pipe element,  $[K]$  represents the stiffness matrix,  $[M]$  indicates the mass matrix, and the subscript  $x$  represents partial differentiation with respect to it.

Using the FEM, the entire flow pipeline is assembled by applying geometric constraints at element nodes and enforcing boundary conditions, yielding the overall mass matrix  $[M]$ , damping matrix  $[C]$ , and stiffness matrix  $[K]$ .

## 2.2 Solving Stochastic Vibration Mathematical Models

The modal analysis method is employed to determine pipeline natural frequencies. Introducing the state vector:

Substituting the state vector into Eq. (1) transforms the equation as follows:

where:

and Eq. (10) can be rewritten as:

The natural frequency of a pipeline depends solely on its inherent structural properties and is independent of external excitation. When considering only the pipeline's self-excited vibration in the absence of external excitation, Eq. (1) simplifies to:

Similarly, Eq. (11) simplifies to:

The solution of Eq. (13) is:

where  $\Psi$  denotes the eigenvector and  $\lambda$  represents the eigenvalue. Its eigenvalues are known to be:

According to complex modal theory, the equation has  $n$  solutions, where  $n$  is the number of degrees of freedom in the system. These solutions are complex eigenvalues,  $\lambda$  ( $i=1,2,\dots,n$ ), with positive imaginary parts. The imaginary part corresponds to the natural frequency  $\omega$  of the flow conduit.

The virtual excitation method is applied to calculate pipeline stress, displacement, and velocity responses. In practice, flow-carrying pipelines in nuclear power plant operations experience intensive vibrations that are difficult to characterize with specific functions, exhibiting distinct randomness. However, field-collected vibration signals follow recognizable statistical patterns, most com-

monly normal distributions. Based on this observation, the stochastic vibration considered in this paper is modeled as stationary Gaussian white noise in acceleration, conforming to a normal distribution.

Based on Eqs. (1), (10), and (11), the vibration equation for a straight flow-carrying pipe under stochastic vibration is expressed as:

The left and right characteristic matrices of Eq. (16) satisfy the following equations:

Based on the modal analysis method, the following decoupling results are obtained:

Substituting Eq. (19) into Eq. (16) and multiplying both sides by  $V$ , we apply the orthogonality of the left and right characteristic matrices to transform Eq. (17) into:

where:

The self-power spectral density of the stochastic vibration is  $S_g(\omega)$ , whose variance is given by:

The vibration response is solved using the virtual excitation method, where the stochastic vibration is defined as:

The solution of Eq. (21) is expressed as:

Substituting Eq. (24) into Eq. (19) yields:

From Eq. (25), the displacement and velocity responses  $y$  and  $\dot{y}$  of the pipeline under stochastic vibration can be obtained. The spectral matrix of the response is then derived as:

The expression for calculating the RMS velocity response is:

The expression for calculating the RMS displacement response is:

Finally, the expression for calculating the RMS stress response is:

### 3. Analysis of the Natural Frequency of Straight Pipes for Fluid Flow

Based on actual operating parameters of the primary loop flow pipeline in a nuclear power plant, as shown in Table 1, a single-factor analysis was conducted with all other parameters held constant to examine the influence of movable support position, pipe length, inner diameter, and wall thickness on natural frequency, as illustrated in Figure 3 [Figure 3: see original paper].

**Table 1. Operating parameters** | Parameter Name | Operating Value | |  
 ————|—————| | Pipe inner diameter (m) | | | Pipe wall thickness (m) | | |  
 Pipe Outer Diameter (m) | | | Pipe length (m) | | | Pipe Elastic Modulus (Pa) |

$1.95 \times 10^{11}$  | Pipeline Density ( $\text{kg} \cdot \text{m}^{-3}$ ) | | Poisson ratio ( ) | | Liquid density ( $\text{kg} \cdot \text{m}^{-3}$ ) |  $1.75 \times 10^7$  | Average fluid pressure (Pa) | | Average fluid velocity ( $\text{m} \cdot \text{s}^{-1}$ ) | |

As shown in Figure 3, the natural frequency first increases and then decreases as the movable support shifts along the pipeline, reaching its maximum at node 8. Increasing the inner diameter and wall thickness also raises the natural frequency. Among all positions, the movable support at node 8 exhibits the largest increase, while node 4 shows the smallest increase and most gradual rise. In contrast, increasing pipe length reduces the natural frequency. Again, the natural frequency is highest at node 8 for the movable support, exhibiting the sharpest decrease, while it shows the slowest decline at node 4.

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## 4. Stochastic Vibration Response Analysis of Flow-Carrying Straight Pipes

With all other parameters held constant, a single-factor analysis method was employed. The random vibration was modeled as Gaussian white noise with a variance of 1000 ( $\text{m}/\text{s}^2$ ) and zero mean.

### 4.1 Pipeline Displacement Response Analysis

The effects of movable support position, pipe length, inner diameter, and wall thickness on displacement response are analyzed, as shown in Figure 4 [Figure 4: see original paper]. The RMS displacement at the pipe outlet increases with pipe length. When the movable support is at node 4, the RMS displacement reaches its maximum and exhibits the steepest increase. Conversely, positioning the support at node 8 results in the minimum RMS displacement with the slowest growth. Increasing the inner diameter and wall thickness reduces the RMS displacement at the pipe outlet. For support at node 4, the mean square displacement is largest and decreases most sharply, while at node 8 it is smallest, with the slowest decrease.

### 4.2 Pipeline Velocity Response Analysis

The effects of movable support position, pipe length, inner diameter, and wall thickness on velocity response are analyzed, as shown in Figure 5 [Figure 5: see original paper]. The RMS velocity at the pipe outlet increases with pipe length. When the movable support is at node 4, the RMS velocity reaches its maximum and exhibits the steepest increase. Conversely, positioning the support at node 8 results in the minimum RMS velocity with the slowest increase. Increasing the inner diameter and wall thickness reduces the RMS velocity at the pipe outlet. The RMS velocity is highest when the support is at node 4, exhibiting the most pronounced decrease, while it is lowest at node 8, showing the slowest decrease.

### 4.3 Pipeline Stress Response Analysis

The influence of movable support positions, pipe length, inner diameter, and wall thickness on stress response is analyzed, as illustrated in Figure 6 [Figure 6: see original paper]. The RMS stress at the pipe outlet decreases with increasing pipe length and inner diameter. When the movable support is at node 8, the RMS stress is highest and decreases most sharply. In contrast, when the support is at node 4, the RMS stress is lowest and decreases most gradually. Increasing wall thickness leads to higher RMS stress at the outlet. For support at node 8, the stress is highest and increases most steeply, while at node 4 it is lowest and rises most slowly.

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## 5. Design Method for Straight Flow Piping

Analysis in Section 3 demonstrates that pipeline structural parameters and support locations significantly affect the vibration response of nuclear power flow-carrying straight pipes under stochastic vibration. However, single-factor analysis cannot capture parameter interactions, whereas actual pipeline vibration responses result from combined effects of multiple factors. Therefore, it is necessary to design primary structural parameters while simultaneously considering movable support locations to minimize pipe displacement, velocity, and stress responses, providing a practical design methodology for pipelines under stochastic vibration conditions.

### 5.1 Design Mathematical Models

Designing structural parameters for nuclear power flow-carrying pipelines under stochastic vibration constitutes a multi-objective, multi-constraint, and multi-extremum problem, for which a multi-objective genetic algorithm is selected. The design problem employs the following mathematical model:

where  $V_{\min}$  denotes the scenario where all subfunctions in the multi-objective function  $f(x) = [f_1(x), f_2(x), \dots, f_n(x)]$  reach their optimal solutions.

Based on engineering practice and Section 3 analysis, three primary structural parameters are selected as design variables: pipe length ( $a$ ), pipe inner diameter ( $d$ ), and pipe wall thickness ( $\delta$ ), i.e.:

The objective is to minimize displacement, velocity, and stress responses under stochastic vibration. As determined in Section 2, the calculation formulas for these responses are given by Eqs. (27), (28), and (29), respectively:

Moreover, the constraint set  $R$  for the design variables is defined as follows:

## 5.2 Design Results and Analysis

Based on the mathematical model, objective function, and constraint set, the parallel selection method is employed to solve the optimization problem. A straight flow-supporting pipe with a fixed left end and movable fixed support serves as a representative example.

As shown in Figures 7(a) and 7(b), both displacement and velocity responses, which exhibit largely similar trends, converge to their RMS values around the 27th generation, yielding the optimal solution. The stress response converges earlier, around the 20th generation, also providing its optimal solution.

**Figure 7 [Figure 7: see original paper]. Variation of the optimal solution for the objective function**

A comparison of pipeline structural parameters before and after optimization is presented in Table 2 .

**Table 2. Genetic algorithm optimization results** | Pipeline Structural Parameters | Initial value | Optimal solution | |-----|-----|-----|  
 || Pipe length (m) || | | Inner diameter (m) | | | Wall thickness (m) | | |

The RMS values of displacement, velocity, and stress response at the outlet before and after design modification are illustrated in Figures 8, 9, and 10 [FIGURE:8-10].

**Figure 8 [Figure 8: see original paper]. RMS displacement at pipe outlet before and after optimization**

**Figure 9 [Figure 9: see original paper]. RMS velocity at pipe outlet before and after optimization**

**Figure 10 [Figure 10: see original paper]. RMS stress at pipe outlet before and after optimization**

**Figure 11 [Figure 11: see original paper]. Natural frequency of piping before and after optimization**

Figures 8, 9, and 10 show that after optimization, the maximum displacement, velocity, and RMS stress at the pipe outlet decreased by 24.83%, 24.54%, and 20.55%, respectively. Recalculating the pipe's natural frequency with optimized parameters revealed a maximum increase of 28.98%, as illustrated in Figure 11. These results indicate that optimizing pipeline structural parameters effectively reduces vibration response under stochastic vibration while simultaneously increasing natural frequency, significantly enhancing pipeline safety and reliability.

## 5.3 Pipeline Design Process

In summary, pipeline vibration response is significantly affected by structural parameters and support locations, rendering traditional design methods insufficient for nuclear power flow pipelines under actual operating conditions. There-

fore, a new design process for straight flow pipelines under stochastic vibration is proposed, as shown in Figure 12 [Figure 12: see original paper].

**Figure 12 [Figure 12: see original paper]. Design process for nuclear power flow-through straight pipes under stochastic vibration**

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## 6. Conclusion

1. A mathematical model and design methodology were established for vibration response of nuclear power plant flow-carrying pipelines under stochastic vibration. Using complex modal analysis and the virtual excitation method, the pipeline's natural frequencies, displacements, velocities, and stress responses were determined.
  2. Research findings show that pipe support positions, pipe length, inner diameter, and wall thickness significantly affect natural frequency, displacement, velocity, and stress response:
    - When the movable support is positioned at node 8, natural frequency and stress response are highest, while displacement and velocity responses are lowest.
    - When the movable support is positioned at node 4, natural frequency and stress response are lowest, while displacement and velocity responses are highest.
    - As pipe length increases, natural frequency and stress response decrease, while displacement and velocity responses increase.
    - As inner diameter increases, natural frequency increases, while displacement, velocity, and stress responses decrease.
    - As wall thickness increases, natural frequency and stress response increase, but displacement and velocity responses decrease.
  3. Using a multi-objective genetic algorithm, structural parameters of a straight flow-conveying pipeline with fixed-end and movable supports were optimized under stochastic vibration. After optimization, maximum displacement, velocity, and RMS stress at the pipeline outlet decreased by 24.83%, 24.54%, and 20.55%, respectively, while maximum natural frequency increased by 28.98%. These results provide a design methodology for straight flow-conveying pipes under stochastic vibration, enhancing performance and reliability in high-vibration environments.
  4. Building upon this research, subsequent studies will investigate nonlinear dynamics, fatigue life prediction, and multimodal vibration reduction design of nuclear power plant flow-carrying pipelines.
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*Note: Figure translations are in progress. See original paper for figures.*

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