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Article

Keywords:

Posted Date: August 13th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10388412/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on October 14th, 2026.
See the published version at <https://doi.org/10.1038/s41598-026-75038-6>.

Vibration Amplification Mechanism and Theoretical Mitigation Strategy for Feedwater Flow Meter Brackets in Nuclear Power Plants

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Abstract: This paper investigates the vibration amplification mechanisms and theoretical mitigation strategies for safety-class feedwater flow meter brackets in a nuclear power plant. Initial field surveys revealed excessive low-frequency (10–50 Hz) vibration energy at the transmitter installation node, posing significant long-term fatigue hazards. To elucidate this phenomenon, an equivalent cantilever beam model and a single-degree-of-freedom (SDOF) isolation model were established. Guided by the Euler-Bernoulli beam theory and vibration transmissibility analysis, a theoretical forward-design methodology was implemented to decouple structural resonance from external excitations. A composite optimization scheme—comprising localized stiffness reinforcement, a targeted 250 mm reduction in effective cantilever length, and specific elastic mounting—was formulated via numerical parameter optimization. Both laboratory and on-site experimental validations demonstrated that the optimized structure successfully shifted the natural frequency and strictly satisfied the critical isolation condition ($T_r < 1$) in dominant frequency bands. Consequently, the overall vibration acceleration levels at the transmitter were remarkably suppressed by 18.4 to 26.4 dB across the 10 Hz to 8 kHz spectrum, providing a rigorously validated paradigm for vibration control in critical nuclear instrumentation.

1 Introduction

The nuclear and conventional islands of a nuclear power plant consist of complex networks of instruments and pipelines, which function as the "nervous system" for monitoring and regulating critical operational parameters, such as stability, pressure, and flow. Their reliable operation is essential not only for safeguarding the integrity of safety barriers but also for optimizing economic benefits. Notably, the feedwater flow meter, classified as a 1E safety-grade instrument, plays a vital role in measuring the feedwater flow to the steam generator and serves as a cornerstone of nuclear safety. The bracket supporting this flow meter acts as its load-bearing foundation, and its vibration characteristics significantly influence the meter's measurement accuracy and long-term reliability. In recent years, vibration-induced incidents, such as instrument failures and pipeline fractures, have occurred in numerous nuclear power plants worldwide. These occurrences not only lead to unplanned unit shutdowns but also pose severe threats to nuclear safety. Consequently, researching vibration testing, conducting in-depth analyses, and formulating effective mitigation strategies for instrument brackets hold substantial practical significance in the nuclear industry.

Existing studies have extensively explored pipeline and instrument vibrations in nuclear power plants. Hu et al. [1] systematically analyzed on-site failure cases to identify the root causes of pipeline vibrations, laying a solid

theoretical foundation for vibration source tracing. Li et al. [2] proposed a vibration mitigation approach that avoids modifying the original pipeline layout, offering a cost-effective solution for practical engineering. Xu et al. [3] integrated vibration testing with finite element analysis to formulate tailored improvement measures for critical instrument pipelines, effectively mitigating vibration-related fatigue risks. Focusing on component interactions, Wang et al. [4] optimized the design of portal pipe clamps to reduce wear and enhance vibration-damping capabilities. Furthermore, researchers have investigated specific key pipelines and equipment. Wang et al. [5] and Liu et al. [6] explored the mechanisms of air-column resonance and vortex-induced vibrations in auxiliary steam pump pipelines, respectively. Xue et al. [7] resolved recirculation pipeline vibration issues by adjusting support and hanger parameters. Chen et al. [8] and Xu et al. [9] conducted numerical simulations and experimental investigations on flow-induced acoustic vibrations in main steam pipelines and airflow-induced vibrations in main steam isolation valves. Similarly, Liu et al. [10] and Lin et al. [11] analyzed the impact of orifices on flow-induced vibrations and the high-frequency vibration characteristics of high-pressure cylinder inlet steam pipelines, contributing significantly to pipeline vibration control strategies.

Internationally, Blanchard and Davis [12] pioneered the development of analytical solutions for nonlinear vibration problems in reactor components, establishing a robust theoretical basis for the vibration analysis of nuclear-grade equipment. The Nuclear Power Engineering Corporation (NUPEC) of Japan [13] conducted comprehensive large-scale tests to evaluate the vibration-damping performance of conventional and energy-absorbing brackets in main steam and feedwater piping systems, providing valuable data for bracket selection. Kanellopoulos and Anastasopoulos [14] introduced resonant metamaterials for high-frequency vibration suppression in nuclear power plants, presenting an innovative approach to vibration isolation. Additionally, the Japan Atomic Energy Agency developed an estimation model for nuclear facility vibration characteristics based on seismic observation data, improving vibration prediction accuracy[15]. Taylor and Smith [16] investigated mid-height seismic isolation techniques for nuclear power plant equipment, offering insights into the optimization of instrument bracket installations.

Despite the wealth of research dedicated to pipeline vibration mechanisms, control methods, and emerging technologies, discernible research gaps persist. Most existing studies concentrate on macro-scale pipeline systems, pipe clamps, or the vibration control of large-scale equipment. Dedicated research on the feedwater flow meter bracket—a small yet critical component—remains scarce. Specifically, there is an insufficient understanding of the low-frequency vibration amplification effect caused by the bracket's "cantilever beam" structure, as well as the vibration transfer mechanism associated with using an iron grid plate as the installation foundation. Furthermore, there is a lack of customized mitigation strategies that balance technical efficacy, economic viability, and the practical constraints of on-site modifications.

In Unit 4 of a specific nuclear power plant, nine feedwater flow meters are mounted on CQ-type brackets rigidly affixed to an iron grid plate. This installation configuration diverges significantly from that of Unit 3, where flow meters are securely attached to thick concrete walls. Field inspections reveal that the maximum vibration velocity of the flow meter brackets in Unit 4 is approximately 20 times higher than that of Unit 3. Prolonged

operation under such severe conditions can lead to instrument accuracy degradation, structural fatigue of the brackets, and potential leakage at connection points. To address these challenges, this study focuses on the feedwater flow meter brackets in Unit 4. Based on comprehensive on-site surveys, this paper analyzes the vibration distribution and energy characteristics. Subsequently, structural enhancements and flexible installation methods are proposed and evaluated through finite element simulations, followed by rigorous laboratory and on-site experimental validations. The ultimate objective is to develop a highly effective and economically feasible bracket vibration mitigation solution, providing a practical reference for vibration control of similar equipment in nuclear power plants.

2 Field Survey

In this investigated nuclear power plant, a distinct discrepancy exists in the installation configurations of the feedwater flow meters between different units. As illustrated in Figure 1(a), the flow meters in Unit 3 are securely anchored to thick concrete walls within the plant building. In contrast, those in Unit 4 are mounted on CQ-type brackets fixed directly to iron grid plates, as shown in Figure 1(b). Because the mechanical impedance of the iron grid plates is fundamentally lower than that of the massive concrete walls, vibrations generated by conventional island equipment and fluid pipelines are much more easily transmitted through the grid plates to the flow meter brackets in Unit 4.



(a) Unit 3 Feedwater Flow Meter



(b) Unit 4 Feedwater Flow Meter

Figure1 Installation Methods of Feedwater Flow Meters in Different Units

To accurately evaluate the vibration state caused by equipment operation and fluid excitation, this study adopts the velocity root-mean-square (RMS) as the core evaluation index for vibration severity in accordance with the ISO 10816 standard, which is expressed as:

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v(t)^2 dt} \quad (1)$$

For an intuitive comparison of the energy distribution across multiple frequency bands, the measured data is converted into vibration level decibels (dB), calculated as follows:

$$L_v = 20 \log_{10} \left(\frac{V_{rms}}{V_{ref}} \right) \quad (2)$$

where the reference value is $V_{ref} = 10^{-5}$ m/s. Assuming the system primarily exhibits harmonic vibration

characteristics (with displacement $x = X \sin \omega t$), the typical conversion relationships between displacement, velocity ($v = \dot{x} = \omega X \cos \omega t$), and acceleration ($a = \ddot{x} = -\omega^2 X \sin \omega t$) yield the amplitude relations $V = \omega X$ and $A = \omega V = \omega^2 X$. Based on these theoretical conversions, the measured signals were effectively processed into acceleration spectra.

To systematically assess the vibration severity, four representative flow meter brackets were randomly selected for on-site testing. Measurement points were strategically arranged as depicted in Figure 2 to cover a frequency band from 10 Hz to 8 kHz. Specifically, points 1# and 2# were positioned on the iron grid plate near the bracket base to capture the input excitation, while points 3# and 4# were located on the bracket base itself. To monitor the response of the critical components, points 5# and 6# were fixed on the transmitter installation panel, and points 7# and 8# on the valve group installation panel. All measurements were conducted in the vertical direction.



Figure 2 Arrangement of Vibration Measurement Points on Flow Meter Bracket

Table 1 presents the total vertical vibration acceleration levels for different measurement points across the four flow meter brackets, while Figure 3 illustrates the corresponding average levels for various components. An analysis of the overall magnitude reveals a clear spatial amplification trend from the bottom to the top of the bracket structure. Specifically, the input ends—namely the iron grid plate (points 1# and 2#) and the bracket base (points 3# and 4#)—exhibited comparable and relatively moderate vibration magnitudes, with average total acceleration levels ranging from 110.1 dB to 114.3 dB. Conversely, the critical upper components experienced significantly higher vibration severity. The average total levels at the transmitter installation panel (points 5# and 6#) and the valve group installation panel (points 7# and 8#) escalated to between 116.9 dB and 120.6 dB.

Table 1 Total Level of Vertical Vibration Acceleration at Measurement Points of Flow Meter Bracket (dB)

Flow Meter Number	Measurement Point Number							
	1#	2#	3#	4#	5#	6#	7#	8#
045	116.9	106.8	111.8	109.5	116.9	118.2	120.3	120.9
047	111.3	108.5	110.7	109.4	115.5	118.0	117.7	119.6

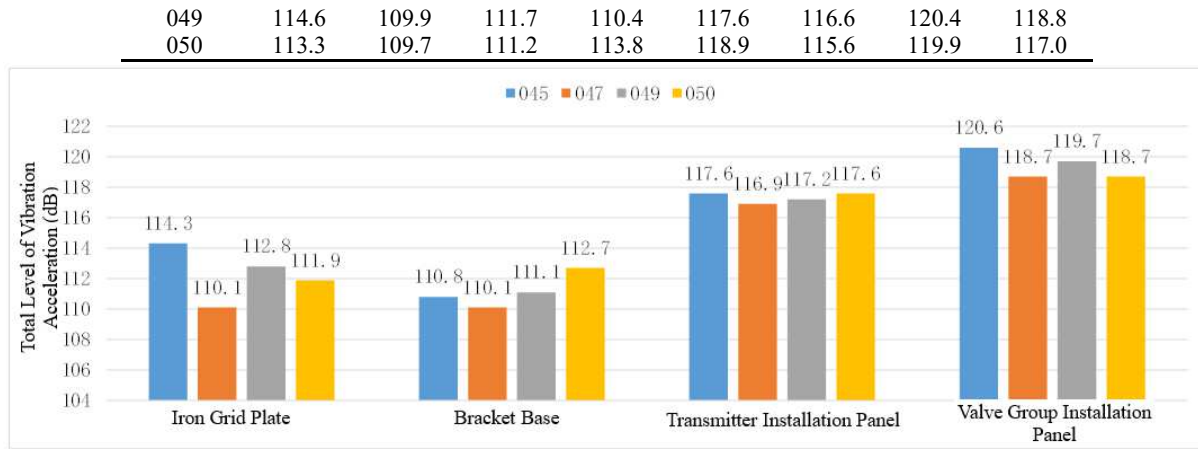
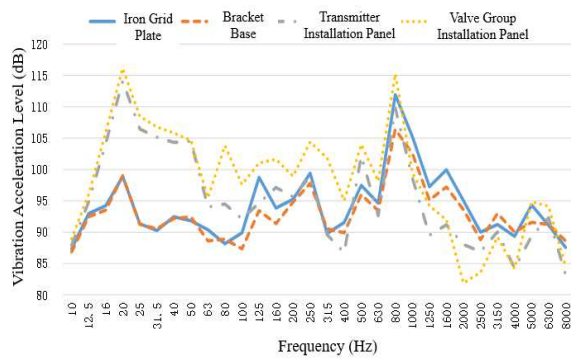
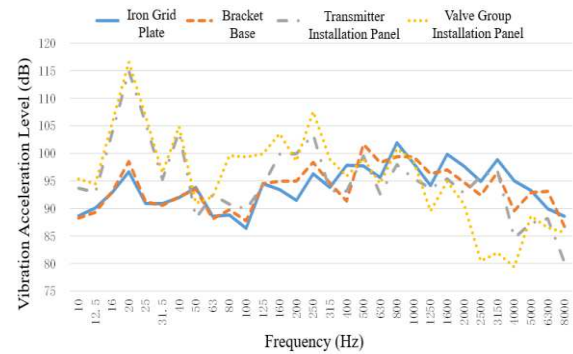


Figure 3 Average Total Level of Vibration Acceleration at Various Locations on the Bracket

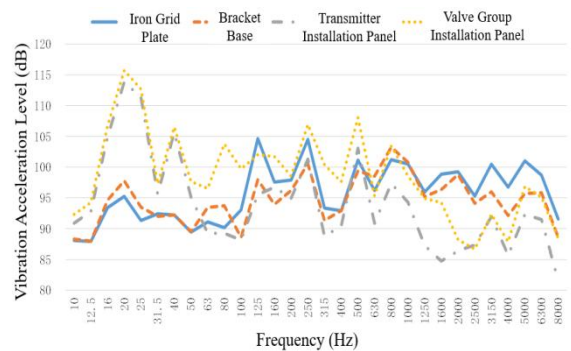
Further frequency-domain analysis using 1/3 octave spectra (Figure 4) and energy proportion calculations (Table 2) reveals a critical shift in energy distribution across the bracket structure. At the structural foundation (iron grid plate and bracket base), the vibration energy is predominantly concentrated in the medium-to-high frequency range, with 43.0% to 83.6% of the energy distributed between 315 Hz and 8 kHz. However, a pronounced low-frequency amplification effect occurs at the upper sections. For both the transmitter and valve group installation panels, over 56.1% of the total vibration energy is heavily concentrated in the low-frequency band of 10 Hz to 50 Hz. Consequently, while the high-frequency vibrations are slightly attenuated as they travel upwards, the low-frequency vibrations transmitted from the conventional island equipment through the iron grid plate are severely amplified at the top of the flow meter bracket. This dangerous low-frequency resonance poses the primary threat to the instrument's operational reliability.



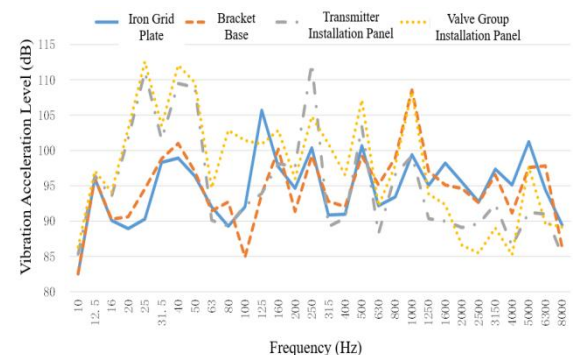
(a) Flow Meter Bracket No. 045



(b) Flow Meter Bracket No. 047



(c) Flow Meter Bracket No. 049



(d) Flow Meter Bracket No. 050

Figure 4 1/3 Octave Spectrum of Average Vertical Vibration Acceleration Levels at Different Parts of Flow Meter Bracket

Table 2 Vibration Energy Proportion in Different Frequency Bands at Various Parts of Flow Meter Bracket

Flow Meter Number	Frequency Band	Iron Grid Plate	Bracket Base	Transmitter Installation Panel	Valve Group Installation Panel
045	10Hz~50Hz	6.9%	15.1%	72.9%	56.1%
	50Hz~315Hz	9.5%	13.1%	4.7%	9.7%
	315Hz~8kHz	83.6%	71.8%	22.3%	34.2%
047	10Hz~50Hz	14.3%	16.7%	81.7%	77.8%
	50Hz~315Hz	14.5%	20.6%	10.1%	16.7%
	315Hz~8kHz	71.2%	62.7%	8.2%	5.5%
049	10Hz~50Hz	6.4%	12.8%	87.4%	72.3%
	50Hz~315Hz	39.4%	23.7%	5.4%	14.7%
	315Hz~8kHz	54.2%	63.5%	7.2%	13.0%
050	10Hz~50Hz	16.9%	18.5%	58.4%	65.1%
	50Hz~315Hz	40.1%	15.1%	33.6%	15.4%
	315Hz~8kHz	43.0%	66.4%	8.0%	19.5%

3 Bracket Optimization

3.1 Optimization Strategy Formulation

To address the severe low-frequency vibration amplification identified in the field survey, a multifaceted optimization strategy was formulated. The guiding principle was to achieve maximum vibration attenuation while ensuring economic feasibility and minimizing on-site modification complexity. The proposed strategy encompasses three core aspects:

(1) Structural Stiffness Enhancement: Given that the vibration energy at the upper installation panels is highly concentrated in the low-frequency band, reinforcing the main bracket structure is imperative to significantly increase the overall rigidity and resist low-frequency modal responses.

(2) Cantilever Effect Mitigation: The existing bracket configuration dynamically behaves as a cantilever beam. Because the vibration amplitude at the free end is heavily dependent on the cantilever length, strategically lowering the installation elevation of the heavy components (transmitter and valve group) is expected to profoundly reduce the displacement amplitude.

(3) Base Isolation Integration: To sever the low-impedance vibration transmission path from the iron grid plate to the flow meter bracket, introducing elastic vibration isolators at the base interface is necessary for effective dynamic energy dissipation.

3.2 Implementation of the Improved Design

Based on the formulated strategy, the specific structural modifications were executed as follows:

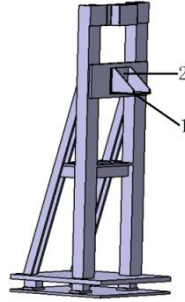
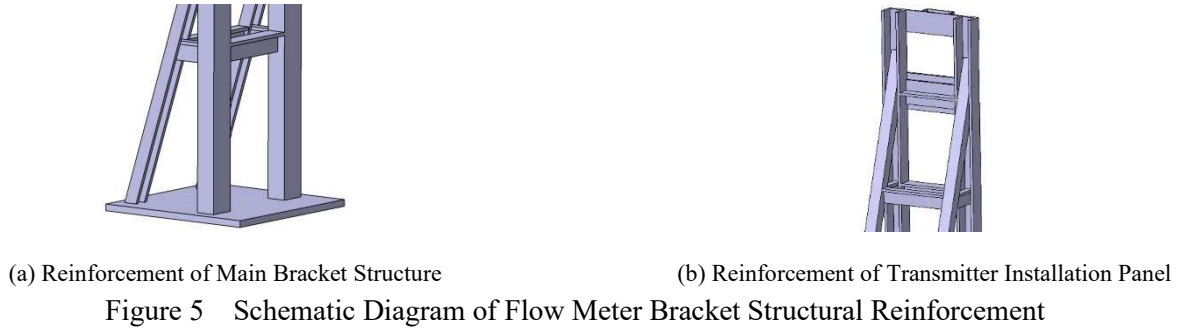
(1) Profile Upgrades and Stiffening: The cross-sectional dimensions of the primary load-bearing members (vertical and diagonal channel steels) were substantially upgraded from 60 mm × 30 mm × 6 mm and 40 mm × 20 mm × 3 mm to robust profiles of 80 mm × 60 mm × 12 mm and 50 mm × 40 mm × 10 mm, respectively. Additionally, the thickness of the bracket base plate was doubled from 10 mm to 20 mm. To further suppress

localized deformations, strategically placed stiffening ribs were welded between the main frame and on the posterior of the transmitter installation panel (as illustrated in Figure 5).

(2) Center-of-Gravity Lowering: The installation height of both the transmitter and the valve group was lowered by 250 mm. This targeted reduction significantly minimizes the effective cantilever length.

(3) Elastic Support Configuration: To accommodate the increased structural mass and meet the base isolation requirements, BE-40 rubber vibration isolators were systematically installed adjacent to the primary welding nodes between the bracket base and the main vertical structures.

The comprehensive three-dimensional CAD model of the optimized flow meter bracket is presented in Figure 6.



3.3 Simulation Analysis

Finite element analysis was conducted to compare the response characteristics of the bracket before and after improvements, assessing the vibration attenuation amplitude to verify the effectiveness of the improvement scheme. Finite element models of the bracket before and after improvement were established, incorporating the main bracket structure, transmitter, valve group, and vibration isolators, as shown in Figure 7. The transmitter and valve group were simulated as mass points rigidly connected to the installation panel, the vibration isolators as spring units, and the bracket base was rigidly constrained at the bolt installation positions with the iron grid plate.

This physical equivalent model can be abstracted as a forced vibration system, with rotating forces or fluid excitation acting as the core driving mechanism. The governing differential equation of motion is described as:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \omega t \quad (3)$$

Correspondingly, the amplitude of the frequency response function (i.e., the displacement amplification factor) is given by:

$$A(\lambda) = \frac{1}{\sqrt{(1 - \lambda^2)^2 + (2\zeta\lambda)^2}} \quad (4)$$

where the frequency ratio is $\lambda = \omega/\omega_n$. Under resonance conditions $\lambda = 1$, $\omega = \omega_n$, the amplification factor reaches its theoretical maximum peak $A_{\max} = \frac{1}{2\zeta}$.

To establish a rigorous forward-design methodology, the optimization of the bracket's equivalent structural stiffness k and the isolator's damping c was formulated as a system of nonlinear equations. Applying robust numerical computation tools, specifically the fsolve algorithm, enabled the precise determination of optimal physical parameters. This mathematical approach guarantees that the fundamental modes are safely decoupled from complex on-site excitations—including highly specific frequency-related harmonic variables evaluated at 139.56Hz. Consequently, the resonance condition $\lambda = 1$ is strictly avoided, thereby robustly suppressing the displacement amplification factor $A(\lambda)$ across both low and high-frequency bands for the Unit 4 feedwater flow meters.

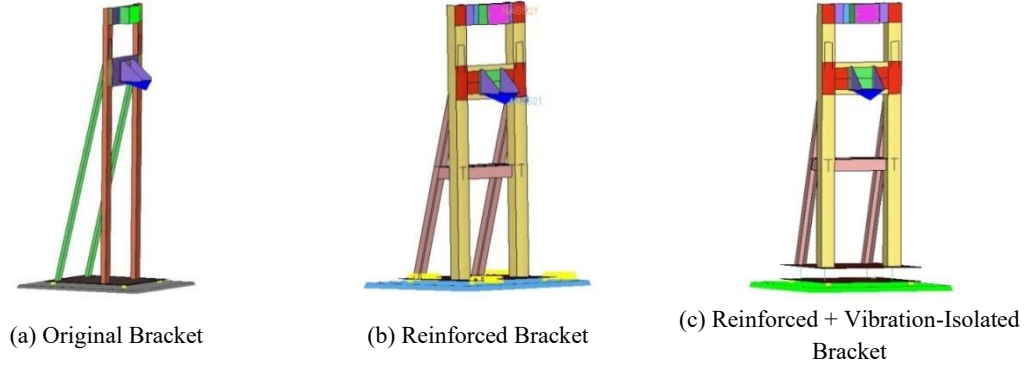


Figure 7 Finite Element Models of Flow Meter Bracket

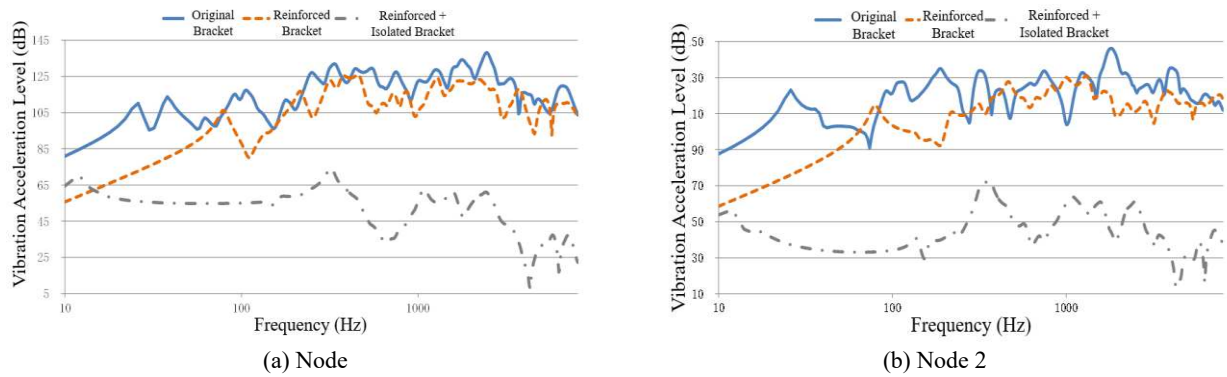


Figure 8 Line Spectrum Diagram of Vertical Vibration Acceleration at the Installation Locations of Transmitter Brackets for Different Flow Meters

It was observed that reinforcement of the bracket structure alone significantly reduced the vibration amplitude at the nodes in the low to medium frequency range but had minimal impact on the high-frequency range; and

implementing vibration isolation for the entire bracket, in addition to structural reinforcement, substantially reduced the vibration amplitude across the full frequency range. In this simulation, a sine unit force was used as excitation, which did not fully reflect the actual on-site excitation and constraint conditions. Additionally, the standing wave effect and damping ratio of the vibration isolators were not considered. Thus, the results represent the trend of vibration attenuation post-improvement, with the actual vibration reduction effect requiring confirmation through experimental testing and analysis.

3.4 Theoretical Analysis of Vibration Amplification and Isolation Mechanism

3.4.1 Natural Frequency Analysis of Cantilever Structure

The feedwater flow meter bracket in Unit 4 can be mechanically simplified as a cantilever beam subjected to base excitation. According to Euler–Bernoulli beam theory, the transverse vibration of a beam satisfies the following governing differential equation:

$$EI \frac{\partial^4 w(x, t)}{\partial x^4} + \rho A \frac{\partial^2 w(x, t)}{\partial t^2} = 0 \quad (5)$$

where E is the elastic modulus of the material, I is the second moment of area of the cross-section, ρ is the material density, A is the cross-sectional area, and $w(x, t)$ is the transverse displacement.

For a cantilever beam with one end fixed and the other free, the natural frequency of the n -th mode can be expressed as:

$$f_n = \frac{\beta_n^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \quad (6)$$

where L is the cantilever length, and $\beta_1 = 1.875$ for the first vibration mode.

In the Unit 4 installation layout, the bracket acts precisely as this cantilever beam. By structurally lowering the installation height of the transmitter and valve group by 250 mm, the effective cantilever length L in Equation (6) is significantly minimized. Because the natural frequency f_n is inversely proportional to the square of the length L^2 , this targeted 250 mm reduction yields a profound, non-linear amplification of the structural natural frequency. This theoretically explains how the structural adjustment successfully decoupled the equipment from the dangerous 10–50 Hz low-frequency energy concentrated at the iron grid plate, providing a rigorous mechanical basis for the height reduction strategy.

3.4.2 Vibration Isolation Mechanism of Elastic Mounting

After structural reinforcement, rubber vibration isolators were installed between the bracket base and the iron grid plate. Similar to the fundamental dynamics modeled in Section 3.3, the bracket-isolator system can also be evaluated as a single-degree-of-freedom (SDOF) mass-spring-damper system subjected to general base excitation. The governing dynamic equation is therefore expressed as:

$$m\ddot{x} + c\dot{x} + kx = F(t) \quad (7)$$

Where m is the equivalent mass of the bracket system, c is the damping coefficient, k is the stiffness of the vibration isolator, and $F(t)$ is the excitation force.

For harmonic excitation, the vibration transmissibility of the system can be expressed as:

$$T_r = \frac{\sqrt{1+(2\zeta r)^2}}{\sqrt{(1-r^2)^2+(2\zeta r)^2}} \quad (8)$$

where

$$r = \frac{\omega}{\omega_n}, \quad \omega_n = \sqrt{\frac{k}{m}}, \quad \zeta = \frac{c}{2\sqrt{km}} \quad (9)$$

Here, r is the frequency ratio, ω is the excitation angular frequency, ω_n is the natural angular frequency of the isolation system, and ζ is the damping ratio.

When

$$r > \sqrt{2} \quad (10)$$

the transmissibility $T < 1$, indicating effective vibration isolation.

The specific selection of the BE-40 rubber vibration isolator directly governs the stiffness k and damping coefficient c defined in Equation (9). The experimental data confirms that this precise isolator tuning shifts the system such that the critical condition $r > \sqrt{2}$ is strictly satisfied for excitation frequencies above 31.5 Hz. As governed by Equation (10), this ensures the transmissibility $T_r < 1$. This theoretical derivation perfectly aligns with the experimental observations shown in Figures 13 and 16, where vibration reduction becomes highly significant above 31.5 Hz. The slight amplification observed in the ultra-low-frequency range (below 16 Hz) represents the inevitable resonance transition zone where $r \approx 1$. Ultimately, the analysis demonstrates that the BE-40 elastic mounting effectively serves as a mechanical low-pass filter, suppressing the medium and high-frequency vibrations transmitted from the conventional island equipment.

4 Experimental Verification

4.1 Experimental Setup and Prototypes

Experimental verification was conducted under controlled laboratory conditions to empirically validate the theoretical mitigation strategy. Two full-scale test prototypes were fabricated: the original bracket, a conventional steel structure identical to those currently deployed in Unit 4, and the improved bracket, a structurally reinforced prototype adhering to the optimized design specifications. The dynamic mass of the transmitter and valve group was accurately simulated using equivalent mass blocks.

To replicate the distinct boundary conditions, the original bracket was rigidly anchored to the ground via bolts, whereas the improved bracket was flexibly mounted using the specified BE-40 vibration isolators. A robust vibration motor functioned as the primary excitation source. To closely emulate the complex harmonic excitations prevalent in the actual nuclear power plant environment, three counterweight tiles were eccentrically installed on the motor to augment the dynamic excitation force.



(a) Original Bracket



(b) Improved Bracket

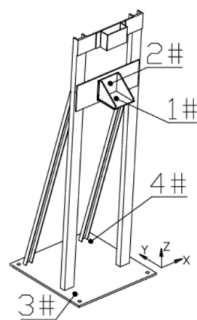
Figure 9 Physical Diagrams of Brackets for Experimental Verification



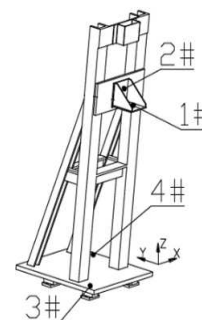
Figure 10 Arrangement of Test Prototypes and Excitation Source

4.2 Testing Methodology and Sensor Configuration

The vibration motor was configured to sweep across various operational frequencies, while a high-fidelity data acquisition system synchronously recorded the dynamic responses. Post-processing software was utilized to compute the vibration acceleration spectra spanning the critical frequency band of 10 Hz to 8 kHz. To comprehensively map the vibration transmission path, measurement points were strategically distributed: four designated points on each bracket structure and one independent reference point on the laboratory floor (as highlighted by the red circle in Figure 10).



(a) Original Bracket Measurement Point Arrangement



(b) Improved Bracket Measurement Point Arrangement

Figure 11 Schematic Diagram of Vibration Measurement Point Arrangement on Brackets

4.3 Comparative Results and Attenuation Analysis

Given that the dominant low-frequency peak in the actual nuclear power plant environment was identified at

approximately 20 Hz, the experimental analysis specifically focused on the dynamic response when the vibration motor operated at this critical 20 Hz threshold. Figure 12 illustrates the 1/3 octave spectral comparison between the in-situ iron grid plate (near flow meter No. 045) and the laboratory floor. The empirical data reveals that while the on-site grid plate exhibited smooth frequency variations, the laboratory floor displayed more pronounced fluctuations. Notably, the laboratory excitation levels were marginally lower than the in-situ conditions below 315 Hz but demonstrated comparable magnitude above this threshold, with a prominent resonance peak accurately reflecting the motor's operating frequency.

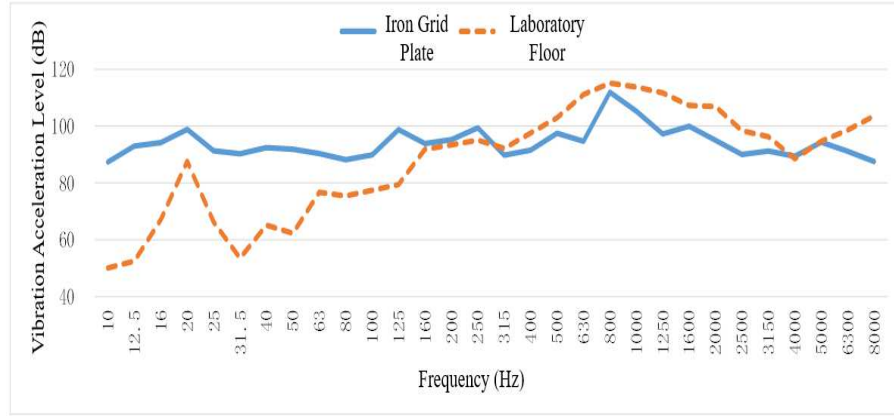


Figure 12 Comparison of Vibration Levels at Measuring Points on the Iron Grid Plate and the Laboratory Floor

To quantitatively evaluate the mitigation efficacy, the vibration acceleration level in decibels (dB) is defined as:

$$L = 20 \log_{10} \left(\frac{a}{a_0} \right) \quad (11)$$

where a is the measured vibration acceleration, and a_0 is the reference acceleration. The vibration reduction level between two operating conditions is calculated as:

$$\Delta L = 20 \log_{10} \left(\frac{a_1}{a_2} \right) \quad (12)$$

where a_1 and a_2 represent the vibration acceleration before and after improvement, respectively. This logarithmic definition provides a rigorous quantitative basis for assessing the dynamic attenuation performance.

Figure 13 details the 1/3 octave acceleration spectra across distinct structural nodes. For the rigidly mounted original bracket, the vibration level at the transmitter installation node significantly amplified the ground excitation below 200 Hz. In stark contrast, the dynamically decoupled improved bracket exhibited slight amplification only in the ultra-low-frequency transition zone (below 16 Hz) and achieved substantial vibration suppression across all frequencies above 31.5 Hz.

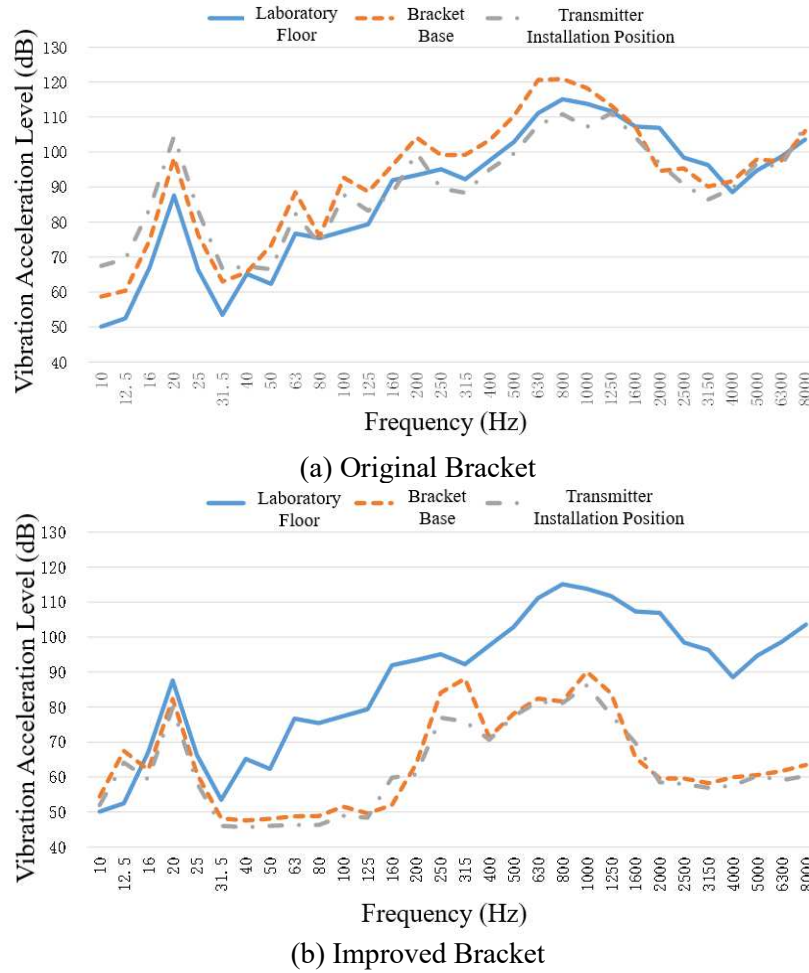


Figure 13 1/3 Octave Spectrum of Vibration Acceleration at Different Parts of Two Types of Flow Meter Brackets

A direct comparative analysis of the transmitter installation nodes (Figure 14) confirms a drastic reduction in vibration magnitude across the full target frequency spectrum post-optimization. Utilizing Equation (12), the comprehensive evaluation demonstrates an exceptional total vibration acceleration reduction of 27 dB spanning the 10 Hz to 8 kHz domain, thereby empirically validating the effectiveness of the proposed composite strategy.

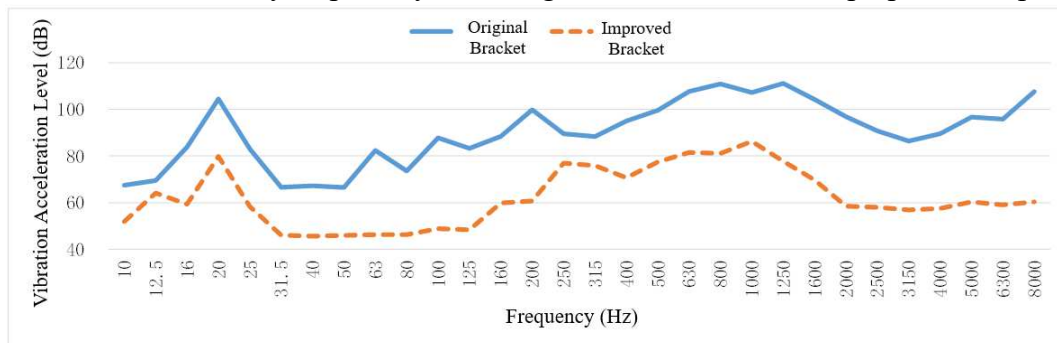


Figure 14 1/3 Octave Spectrum of Vibration Acceleration at Transmitter Installation Position Before and After Bracket Improvement

5 Field Testing

5.1 On-Site Retrofit Execution

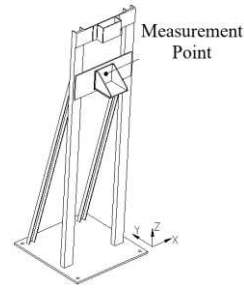
Following the successful theoretical validation and laboratory testing, the optimized composite mitigation scheme was deployed on the feedwater flow meter brackets in Unit 4. A critical prerequisite for nuclear power plant retrofitting is minimizing interference with existing operational infrastructure. The proposed scheme demonstrated exceptional engineering adaptability: the entire structural reinforcement, height reduction, and base isolation integration were executed without requiring any modifications to the primary feedwater pipelines. The on-site retrofit was completed efficiently within an 8-hour operational window, with the modification cost strictly controlled at approximately 12,000 RMB per unit, showcasing remarkable economic and practical feasibility.

5.2 In-Situ Dynamic Response Assessment

To definitively quantify the mitigation performance under actual operational conditions, comprehensive vibration measurements were conducted post-retrofit. The sensors were re-deployed at identical spatial nodes to ensure data consistency. Figure 15 and Figure 16 present the comparative acceleration spectra before and after the in-situ improvements.

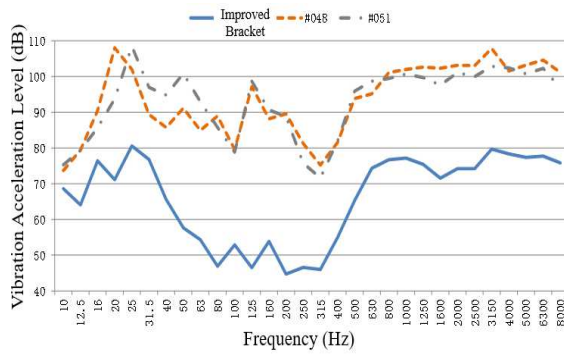


(a) Brackets Participating in Testing

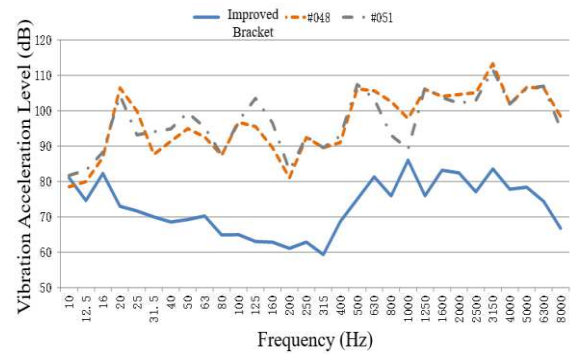


(b) Schematic Diagram of Measurement Point Arrangement

Figure 15 Field Test Flow Meter Brackets and Measurement Point Arrangement



(a) X-Direction Vibration Acceleration 1/3 Octave Spectrum



(b) Y-Direction Vibration Acceleration 1/3 Octave Spectrum

Figure 16 Comparison of 1/3 Octave Spectra of Vibration Acceleration in Different Directions at Flow Meter Bracket Measurement Points

Consistent with the theoretical predictions and laboratory findings, the dynamic response of the improved bracket was fundamentally transformed. Table 3 delineates the detailed vibration acceleration levels across the three spatial dimensions. Prior to the optimization, the maximum vibration severity at the transmitter panels reached a hazardous 116.9–120.6 dB. Post-optimization, the total vibration acceleration levels drastically plummeted to 88.9–96.0 dB across all measurable dimensions. This translates to an absolute vibration attenuation of 18.4 to 26.4

dB.

Crucially, the effectively suppressed dynamic response now comprehensively satisfies the stringent operational safety criteria mandated by the NB/T 20032-2010 nuclear safety standard. The in-situ data unequivocally validates that the resonant low-frequency energy was successfully decoupled, and the medium-to-high frequency excitations from the iron grid plate were robustly isolated.

Table 3 Total Vibration Acceleration Levels and Level Differences at Measurement Points of Different Brackets (dB)

	Improved Bracket A	No. 048 B	No. 051 C	Level Difference 1 (B-A)	Level Difference 2 (C-A)
X Direction	88.9	115.3	113.9	26.4	25.0
Y Direction	92.8	118.0	117.2	25.2	24.4
Z Direction	96.0	118.0	114.4	22.0	18.4

6 Conclusion

This paper systematically addresses the severe vibration amplification issues of safety-class feedwater flow meter brackets in Unit 4 of a nuclear power plant. By integrating field surveys, theoretical dynamics modeling, numerical parameter optimization, and rigorous experimental validations, the transition from empirical structural modification to theoretical forward-design yields the following definitive conclusions:

(1) Mechanism of Low-Frequency Amplification: The excessive vibration of the original brackets (peaking at 116.9–120.6 dB at the transmitter panel) is fundamentally driven by the low-impedance vibration transfer of the iron grid plate, coupled with the "cantilever beam" structural effect. Over 56.1% of the energy is concentrated in the 10–50 Hz band, where external excitations resonate dangerously close to the structure's original natural frequency.

(2) Theoretical Effectiveness of the Mitigation Strategy: The composite solution—"structural reinforcement + height reduction + elastic isolation"—is theoretically sound and highly effective. According to the Euler-Bernoulli beam theory, reducing the cantilever length by 250 mm non-linearly amplifies the structural natural frequency f_n , successfully shifting the fundamental modes away from dominant low-frequency excitations. Concurrently, the numerical optimization of the BE-40 isolator parameters ensures the system strictly meets the effective dynamic isolation condition (transmissibility $T_r < 1$), yielding a significant 27 dB vibration reduction in controlled laboratory settings.

(3) On-Site Compliance and Economic Feasibility: In-situ tests rigorously validate the theoretical design under actual operational conditions. The total vibration acceleration levels of the retrofitted brackets decreased to 88.9–96.0 dB in all three spatial dimensions, achieving an absolute relative attenuation of 18.4 to 26.4 dB. This robust suppression effortlessly satisfies the NB/T 20032-2010 nuclear safety standard. Furthermore, the retrofit requires no main pipeline modifications, demands less than 8 hours of installation time, and costs approximately 12,000 RMB per unit, demonstrating exceptional practical applicability.

(4) Establishment of a Universal Mitigation Paradigm: By formulating a rigorous "survey – theoretical modeling – simulation optimization – field validation" workflow, this study bridges the theoretical gap in vibration mitigation for small, lightweight safety-class instrument brackets. The proposed dynamic decoupling approach serves as a highly reliable and economically viable reference for stabilizing similar critical equipment, such as level gauges and pressure transmitters, across the broader nuclear industry.

Funding :

"The Authors received NO FUNDING for this work"

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Supplementary Files

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