

RESEARCH ARTICLE

Development of Computational Tool for Flow-Induced Vibration Prediction and Structural Risk Assessment in Shell and Tube Heat Exchangers

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ABSTRACT: This work introduces MAK-FIV, a specialized computational tool developed for the systematic identification and analysis of flow-induced vibration phenomena in shell-and-tube heat exchangers. The software is designed to evaluate the four principal excitation mechanisms known to govern vibratory behavior in such systems: fluid-elastic instability, turbulent buffeting, acoustic resonance, and vortex shedding. By integrating established empirical correlations with fundamental vibration theory, the tool provides a structured assessment of six critical failure modes that commonly arise from these flow-related excitations. These include tube wear, mid-span collisions, fatigue failure, excessive noise generation, pressure drop, and the potential for stress corrosion cracking. The primary objective of MAK-FIV is to enable early diagnosis of vibratory damage, thereby supporting the development of more reliable and thermally efficient heat exchanger designs. Through a systematic classification of excitation mechanisms and a corresponding risk evaluation, the tool offers engineers a practical means to identify potential vulnerabilities during the design phase. This approach facilitates the implementation of targeted mitigation strategies, which can lead to reduced maintenance interventions, improved operational uptime, and enhanced long-term equipment integrity. The tool bridges the gap between theoretical vibration analysis and applied engineering design, offering a unified platform for managing the complexities of fluid-structure interaction in heat exchanger applications.

Keywords: Shell-and-Tube Heat Exchanger, Flow-Induced Vibration (FIV), Fluid-Elastic Instability, Structural Risk Assessment, Computational Modeling, Damage Mechanism Analysis.

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1. INTRODUCTION

Vibrations induced by fluid flow remain a persistent and significant concern for the designers and maintenance engineers of shell-and-tube heat exchangers. This concern is particularly acute in high-demand industries such as power generation, petrochemical processing, and refinery operations,

where the reliability and thermal performance of these critical pieces of equipment are directly tied to overall plant safety and productivity. The complex interplay between the shell-side crossflow and the flexible tube bundle gives rise to a range of vibratory phenomena that, if not properly accounted for during the design phase, can lead to premature equipment failure and costly unscheduled shutdowns [1, 2]. The root cause of these vibrations lies in the transfer of kinetic energy from the fluid to the tube structures, a process that is more pronounced in shell-and-tube geometries due to the nature of fluid-structure interaction. The primary excitation mechanisms responsible for this energy transfer are fluid-elastic instability, vortex shedding,

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turbulent buffeting, and acoustic resonance [3–8]. Each mechanism arises from a distinct physical process and poses a unique set of risks to the mechanical integrity of the tube bundle. Fluid-elastic instability (FEI) is widely recognized as the most destructive of these mechanisms. It manifests as large-amplitude, self-excited vibrations that occur once the cross-flow velocity exceeds a critical threshold. This phenomenon is distinct from other excitation sources because it does not rely on an external periodic forcing function; instead, the tube motion itself modulates the fluid forces, creating a self-sustaining oscillation that can rapidly lead to catastrophic tube failure [2, 9–13]. The critical velocity at which FEI initiates is governed by parameters such as tube bundle geometry, including pitch ratio and arrangement, as well as the system's damping characteristics. Compounding the challenge, recent studies have highlighted the importance of multimode coupling, demonstrating that in nonuniform flow fields, the interaction of multiple vibration modes can lower the expected instability threshold by as much as forty percent compared to predictions based on single-mode analysis [14]. This finding underscores a critical limitation of simplified analytical approaches. Further complicating accurate prediction is the persistent difficulty in obtaining reliable damping estimates, with experimental measurements and theoretical predictions often differing by a factor of four [9, 13]. The influence of tube-support interactions and nonuniform flow conditions has thus driven recent efforts toward developing hybrid models that combine structural analysis with computational fluid dynamics to achieve greater predictive accuracy [9, 13, 14]. Vortex shedding presents another significant excitation mechanism, characterized by the periodic formation and detachment of vortices on alternating sides of a tube. This process creates oscillatory forces at a distinct frequency. The greatest risk occurs when this vortex shedding frequency coincides with, or "locks-in" with, one of the tube's natural frequencies, leading to resonant amplification of the vibration amplitude. Research on tube arrays has shown that these vortex-induced vibrations can produce significant mechanical responses, particularly in the first few rows of tubes or in bundles subjected to liquid cross-flow, where the distinction between narrowband vortex shedding peaks and broadband turbulent energy becomes a critical factor in assessing potential damage [3]. In contrast to the periodic nature of vortex shedding, turbulent buffeting results from the random, stochastic pressure fluctuations inherent in turbulent flow. This mechanism subjects tubes to persistent, low-amplitude vibrations across a broad

frequency range. While these vibrations are generally of lower energy than those caused by FEI or resonant vortex shedding, their continuous presence during operation can lead to cumulative fretting wear at tube support points, posing a significant long-term threat to reliability [2, 3]. Acoustic resonance introduces yet another layer of complexity, occurring when the frequency of vortex shedding coincides with an acoustic mode of the shell cavity. This coincidence can generate large-amplitude pressure pulsations and high-intensity noise. The installation of acoustic baffles has proven effective in mitigating this issue by altering the modal distribution of the cavity and providing damping, with potential reductions in vibration levels of up to 20 decibels [6, 7]. The uncontrolled vibration resulting from these mechanisms initiates a cascade of potential damage modes. These include mid-span collisions, where large tube amplitudes lead to contact between adjacent tubes or between tubes and baffles, causing high rates of fretting wear [3]. This fretting wear is exacerbated by cyclic vibration frequencies and is highly sensitive to material compatibility and operating temperatures, particularly under high-load or elevated temperature conditions [7, 8, 10–12]. Fatigue failure represents another direct consequence, as repeated cyclic stresses, if they exceed the material's endurance limit, can lead to crack initiation and propagation. Excessive noise, often associated with gas flows, is frequently linked to acoustic resonance and can reach levels that pose safety and environmental compliance challenges [6, 13, 15, 16]. Furthermore, vibration can indirectly contribute to issues such as increased pressure drop and stress corrosion cracking by disrupting protective oxide layers or accelerating the transport of corrosive species to fresh metal surfaces. The structural behavior becomes especially complex in multiphase flow or uneven fluid distribution scenarios, where effective damping is significantly reduced. Industrial standards, such as those from TEMA and ASME, now emphasize the necessity of rigorous vibration assessment, highlighting the value of software-based prediction tools in developing designs resistant to flow-induced failure [10, 17–22]. The novelty of the present work lies in the development of MAK-FIV, a dedicated computational tool designed to integrate the assessment of these four primary excitation mechanisms with a systematic evaluation of their resultant damage modalities within a single, unified platform. Unlike conventional approaches that often treat vibration analysis and damage assessment as separate exercises, MAK-FIV is structured to directly correlate the predicted vibratory response, stemming from fluid-elastic instability, vortex shedding, turbulent buffeting, and acoustic resonance, with

specific, quantifiable failure risks such as tube wear thickness, fatigue life, mid-span collision potential, excessive noise, pressure drop, and stress corrosion susceptibility. This integrated framework, grounded in established empirical correlations and fundamental vibration theory, is intended to bridge the gap between theoretical prediction and practical design, providing engineers with a tool for early risk diagnosis and the development of targeted mitigation strategies. By enabling a more holistic view of the fluid-structure interaction problem, MAK-FIV aims to address the critical research gap where current methods often fall short in managing the complex interplay between multiple vibration phenomena and their potential for damage.

2. METHODOLOGY

The analytical framework underpinning the MAK-FIV tool is constructed upon established empirical correlations and the recommended practices outlined in industry standards, including those from the Tubular Exchanger Manufacturers Association (TEMA) and the American Society of Mechanical Engineers (ASME). The methodology is designed to provide a systematic evaluation of the four principal flow-induced vibration excitation mechanisms: fluid-elastic instability, vortex shedding, turbulent buffeting, and acoustic resonance. Beyond the prediction of these vibrational phenomena, the tool extends its analysis to quantify their potential consequences through the assessment of six critical damage modalities: tube wear damage thickness, mid-span collision, fatigue failure, excessive noise generation, pressure drop, and the risk of stress corrosion cracking. The core of the vibration assessment process involves calculating key parameters for each excitation mechanism and comparing them against established allowable limits or threshold criteria to determine the structural integrity and operational safety of the tube bundle.

2.1 Determination of Tube Bundle Dynamic Characteristics

The initial phase of the assessment focuses on establishing the fundamental dynamic properties of the tube bundle. This begins with the calculation of the tube mass per unit length, which accounts for the mass of the tube itself, the mass of the fluid contained within it, and the added mass effect from the surrounding shell-side fluid that moves in concert with the tube during vibration. Following this, the area moment of inertia of the tube cross-section is

computed based on its outer and inner diameters. With these parameters established, the fundamental natural frequency of the tube is then determined. This calculation considers the tube's flexural rigidity, its mass per unit length, and the span length between supports, taking into account the boundary conditions imposed by the tube sheets and baffles. This natural frequency serves as a critical reference point for assessing the potential for resonance with various excitation mechanisms.

2.2 Fluid-Elastic Instability Analysis

Fluid-elastic instability (FEI) is evaluated as the most critical excitation mechanism due to its capacity for generating self-excited, large-amplitude vibrations that can lead to rapid structural failure [2, 9, 13]. The analysis follows a methodology rooted in the determination of a critical cross-flow velocity. The first step involves calculating a mass-damping parameter, a dimensionless quantity that characterizes the system's inherent ability to dissipate vibrational energy through a combination of structural and fluid damping. Using this parameter, along with the tube bundle geometry, specifically the pitch ratio and tube arrangement, the FEI critical velocity is computed based on established instability criteria. This critical velocity represents the threshold beyond which the system becomes unstable, and self-excited oscillations will grow. The design is considered acceptable if the actual shell-side cross-flow velocity is less than this calculated critical velocity, with a suitable safety margin applied.

2.3 Vortex Shedding and Acoustic Resonance Assessment

Vortex shedding is analyzed as a source of periodic forcing. The vortex shedding frequency is calculated based on the Strouhal number, a dimensionless parameter characteristic of the tube array pattern, and the cross-flow velocity. The potential for resonance is then assessed by calculating a vortex shedding ratio, which is the ratio of the vortex shedding frequency to the tube's fundamental natural frequency. A ratio near unity indicates a lock-in condition, where resonant amplification can occur, and such operating conditions are typically avoided to prevent excessive vibration amplitudes [3]. Acoustic resonance analysis is performed concurrently, particularly relevant for gas flows. The natural frequencies of the shell-side cavity are determined for both axial and transverse acoustic modes. The axial acoustic frequency depends on the speed of sound in the shell-side fluid and the characteristic length of the shell, while the transverse or angular acoustic frequency

is a function of the same speed of sound and the tube pitch. Acoustic resonance is predicted if the vortex shedding frequency coincides with, or is harmonically related to, one of these calculated acoustic natural frequencies, a condition that can generate high-intensity pressure pulsations and noise [6].

2.4 Turbulent Buffeting Analysis

Turbulent buffeting is treated as a random, broadband excitation mechanism. The analysis focuses on quantifying the root-mean-square (RMS) magnitude of the fluctuating lift force generated by turbulent pressure variations in the flow across the tube span. While this excitation is not typically resonant in nature, the methodology accounts for its continuous, low-amplitude forcing. The calculated RMS force is used in subsequent assessments of long-term fretting wear, as the persistent nature of turbulent buffeting is a key contributor to cumulative fatigue and wear damage at tube support points [2, 3].

2.5 Damage Modality Evaluation

Following the analysis of excitation mechanisms, the methodology proceeds to evaluate the potential for specific damage modes. For mid-span collision, the maximum static deflection of the tube under its own weight is calculated and compared to half the diametral clearance to adjacent tubes or baffles. Exceeding this clearance indicates a risk of impact and fretting wear during operation [3]. Tube wear damage thickness is estimated using a modified Archard wear model. This approach relates the volume of material lost to the normal load, sliding distance, and a wear coefficient that is informed by material compatibility and operating conditions. The volumetric wear is converted to a one-dimensional wear depth by dividing by the nominal contact area at the tube support. Acceptable wear is defined by a criterion ensuring sufficient remaining wall thickness to maintain structural integrity, typically a percentage of the original thickness [7]. Fatigue failure assessment is performed by comparing the cyclic bending stress induced by the dominant excitation mechanism to the material's endurance limit. If the induced stress remains below this limit, infinite fatigue life is assumed. Excessive noise levels are evaluated using an empirical approximation relating sound pressure level to flow velocity, with the results checked against permissible limits for operator safety and environmental compliance. The pressure drop across the tube bundle is also calculated, serving not only as a performance metric but also as an indicator of flow velocity magnitude

and, consequently, the overall vibration potential. Finally, the risk of stress corrosion cracking is considered by evaluating whether the combined effects of cyclic stress and a corrosive environment create conditions conducive to crack initiation, with reference to standard material-environment compatibility guidelines.

3. RESULTS AND DISCUSSIONS

To demonstrate the functionality and practical application of the MAK-FIV tool, a representative shell-and-tube heat exchanger configuration was selected as a case study. The unit under consideration is a fixed-tube-sheet design conforming to the CEM TEMA classification, featuring a type C front channel with an integral tube sheet and detachable cover, a single-pass type E shell, and a type M fixed tube sheet at the rear. The heat exchanger contains straight tubes of 19.5 mm outer diameter and 1.27 mm wall thickness, with a tube length of 3580 mm. The shell-side fluid is water at ambient conditions, flowing at a velocity of 0.5 m/s. The tube bundle is supported by baffles with a mid-span spacing of 470 mm and inlet and outlet spacings of 1031.75 mm. A comprehensive list of the design parameters used for the analysis is provided in Table 1.

Table 1. Design parameters for the CEM TEMA style shell-and-tube heat exchanger used in the case study.

Parameter	Value
Tube material	Carbon Steel
Tube outside diameter (mm)	19.5
Tube wall thickness (mm)	1.27
Tube length (mm)	3580
Tube material density (kg/m ³)	8030
Allowable stress (N/mm ²)	54.1
Modulus of elasticity (N/mm ²)	1.95×10^5
Baffle thickness (mm)	15.875
Tube-to-baffle clearance (mm)	0.49276
Tube pitch (mm)	23.8125
Shell-side fluid density (kg/m ³)	1000
Tube-side fluid density (kg/m ³)	1000
Cross-flow velocity (m/s)	0.5
Inlet baffle spacing (mm)	1031.75
Mid-span baffle spacing (mm)	470
Outlet baffle spacing (mm)	1031.75

The results generated by the MAK-FIV tool for this configuration are presented and discussed in detail below, with each excitation mechanism and damage modality examined in turn. Figure 1 exhibits the flow chart for the vibration evaluation methodology for the shell and tube type heat exchangers.

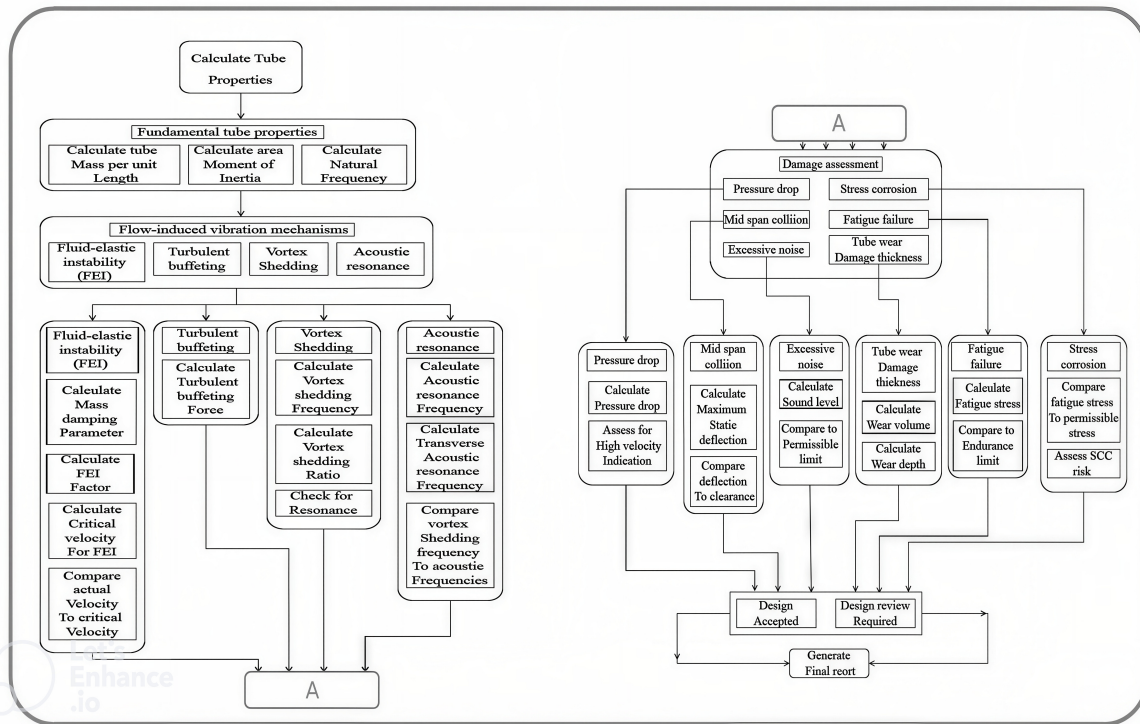


Fig. 1. Flowchart illustrating the stepwise vibration evaluation methodology implemented in the MAK-FIV tool for shell-and-tube heat exchangers.

3.1 Dynamic Characteristics and Natural Frequency

The fundamental natural frequency of the tube was computed by the MAK-FIV tool to be 7.189 Hz. This value is notably lower than typical frequencies observed in many industrial shell-and-tube heat exchanger designs. A reduced natural frequency is indicative of increased tube flexibility, which in this configuration is influenced by the relatively long unsupported span lengths, particularly at the inlet and outlet sections where baffle spacing exceeds one meter. Lower natural frequencies inherently increase the susceptibility of the tube bundle to excitation from flow-induced sources, as the range of frequencies over which resonance can occur becomes broader and more readily overlaps with typical excitation frequencies [1]. This finding warrants careful attention, as mechanisms such as vortex shedding and turbulent buffeting generate forces across a frequency spectrum that often includes lower frequency components. The tool's ability to highlight this vulnerability early in the design process provides engineers with an opportunity to consider design modifications, such as reducing baffle spacing or increasing tube wall thickness, before fabrication.

3.2 Fluid-Elastic Instability Assessment

The fluid-elastic instability ratio computed by MAK-FIV was found to be 0.12. This ratio represents the relationship between the actual cross-flow velocity and the calculated critical velocity for the onset of fluid-elastic instability. With a value substantially below the threshold of 1.0, the analysis indicates that the current design operates well within the stable regime. Fluid-elastic instability is widely recognized as the most destructive excitation mechanism in tube bundles because it produces self-excited, large-amplitude oscillations once the critical velocity is exceeded [2, 9, 13]. The substantial safety margin reflected by the ratio of 0.12 suggests that even with potential uncertainties in damping estimates or flow distribution, the design is unlikely to experience the catastrophic vibrations associated with FEI under normal operating conditions. This outcome confirms that the combination of tube geometry, flow velocity, and system damping is adequately managed for this particular mechanism.

3.3 Vortex Shedding and Resonance Potential

The vortex shedding ratio, which compares the

vortex shedding frequency to the tube's natural frequency, was also calculated to be 0.12. This value indicates a significant separation between the forcing frequency generated by periodic vortex formation and the tube's natural frequency. In practical terms, this means that the energy transfer from the fluid to the tube structure through vortex shedding is minimal, and the conditions for resonance, where the two frequencies coincide or lock-in, are not present [3]. The safe margin observed here is consistent with the low cross-flow velocity of 0.5 m/s, which results in vortex shedding frequencies that are considerably lower than the tube's natural frequency. While the current configuration is not at risk from resonant vortex shedding, the tool's output serves as a useful baseline for assessing how changes in flow velocity or tube geometry could alter this margin.

3.4 Turbulent Buffeting Analysis

For the given flow conditions, the tool's turbulent buffeting analysis produced a root-mean-square fluctuating lift force that was relatively modest. Turbulent buffeting, unlike vortex shedding or fluid-elastic instability, does not typically produce large-amplitude vibrations but instead contributes to continuous, low-energy excitation [2, 3]. The primary concern associated with this mechanism is not immediate failure but rather cumulative fretting wear at tube support points over extended periods of operation. The results from the case study indicate that while turbulent buffeting forces are present, their magnitude is within a range that would not accelerate wear beyond acceptable limits, provided that the tube-to-baffle clearances and material compatibility are maintained as specified.

3.5 Acoustic Resonance Evaluation

Acoustic resonance analysis was performed to evaluate the potential for standing pressure waves within the shell cavity. Given that the shell-side fluid is water, which has a relatively high speed of sound and provides substantial damping, the likelihood of sustained acoustic resonance is considerably lower than in gas-flow applications [6]. The calculated axial and transverse acoustic frequencies were found to be well-separated from both the vortex shedding frequency and the tube's natural frequency. Consequently, the analysis did not predict any conditions conducive to acoustic resonance. This outcome is consistent with the expected behavior for liquid-shell-side heat exchangers, where acoustic effects are generally less problematic. However, the tool's inclusion of this analysis remains valuable

for completeness and for cases involving gas or two-phase flow.

3.6 Damage Modality Evaluation

3.6.1 Tube Wear Damage Thickness

The predicted tube wear damage thickness was calculated to be 1.2699 mm. This value represents the estimated material loss at the tube-baffle interface due to fretting wear over the design life, based on the Archard wear model [7]. With an original tube wall thickness of 1.27 mm, the predicted wear thickness would result in a remaining wall thickness that approaches the minimum acceptable structural limit. The result suggests that while the design does not immediately violate wear criteria, it leaves very little margin for operational variations or uncertainties in wear coefficient assumptions. In practice, this level of wear would warrant careful consideration, as any increase in flow velocity, misalignment, or changes in operating conditions could accelerate wear and compromise tube integrity.

3.6.2 Mid-Span Collision Risk

The static deflection of the tube at its mid-span was computed and compared to the available diametral clearance to adjacent tubes and baffles. The calculated deflection was found to be less than half the clearance, indicating that under static conditions, the risk of mid-span collision is minimal. However, it is important to recognize that dynamic deflections during operation can be significantly larger than static deflections, particularly if any resonant conditions were to arise. The current assessment provides a baseline, but a more comprehensive dynamic analysis would be required to fully evaluate collision risk under all operating scenarios.

3.6.3 Fatigue Failure Assessment

The fatigue failure output from the tool was reported as 0 MPa, indicating that the cyclic stress amplitude induced by the primary excitation mechanisms was calculated to be negligible. At first glance, this might suggest an absence of fatigue risk. However, this result must be interpreted with caution. The zero stress output is largely attributable to the fact that the current analysis is dominated by single-mode, steady-state excitation where the predicted response amplitudes were very low. In reality, fatigue damage can accumulate through a combination of mechanisms, including transient events during startup and shutdown, as well as

multimode interactions that are not fully captured by simplified models [14]. Therefore, while the result is reassuring, it should not be interpreted as definitive proof of infinite fatigue life, and ongoing monitoring or more detailed analysis may be warranted for critical applications.

3.6.4 Excessive Noise and Pressure Drop

The estimated sound pressure level generated by the flow was calculated to be within acceptable limits for operator safety and environmental compliance, consistent with the low flow velocity and liquid medium. Similarly, the predicted pressure drop across the tube bundle was found to be within typical design ranges, confirming that flow velocities are not excessively high from a performance perspective.

3.7 Visualization of Results

Table 2 presents the vibration analysis results table generated by MAK-FIV for the case study.

Table 2. Tabular output from MAK-FIV summarizing the calculated vibration parameters and damage indicators for the case study configuration.

Vibration Data Summary	
Parameter	Value
Natural Frequency	7.189 Hz
Average Span Length	0.498 m
Tube Pitch	23.8125 mm
Tube Gap	4.312 mm
FEI Constant	3.5
Lift Coefficient	0.1
Added Mass Factor	1.915
Log Decrement	0.1
Analysis Results	
Frequency (Hz)	7.189
Gap Velocity Ratio	1.0373
Max Vortex Shedding Amplitude	0.0582 mm
Vortex Shedding Ratio	0.0135

This tabular output consolidates all key calculated parameters, including the natural frequency, fluid-elastic instability ratio, vortex shedding ratio, predicted wear thickness, and fatigue stress. The organization of this data allows engineers to quickly identify which parameters are within acceptable ranges and which approach or exceed thresholds. The figure demonstrates the tool's capability to present complex analytical outputs in a structured, readily interpretable format.

Figure 2 illustrates the vibration risk versus flow velocity graph. This graphical output shows

how the fluid-elastic instability ratio varies with cross-flow velocity, providing a visual representation of the safety margin relative to the critical velocity threshold. In this case, the graph clearly indicates that the operating point lies well within the stable region, with the ratio increasing gradually as velocity increases. Such a visualization is valuable for sensitivity analysis, enabling engineers to understand how changes in flow conditions would affect stability margins.

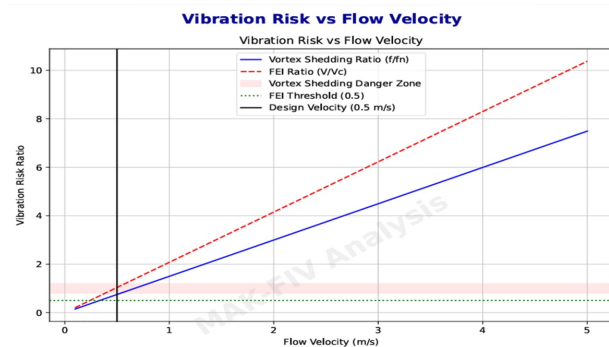


Fig. 2. Variation of the fluid-elastic instability ratio with shell-side cross-flow velocity, showing the operating point relative to the critical instability threshold.

Figure 3 displays the displacement versus time graph.

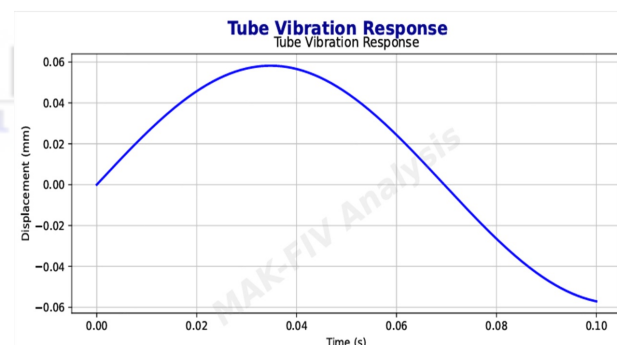


Fig. 3. Time-domain displacement response of the tube under the combined influence of flow-induced excitation mechanisms, as predicted by MAK-FIV.

This plot simulates the time-domain response of the tube under the combined influence of the identified excitation mechanisms. The graph shows a relatively steady, low-amplitude oscillation, consistent with the absence of resonant conditions or fluid-elastic instability. The amplitude remains well within the clearance limits, visually confirming the stability predicted by the numerical results. Table 3 provides the acceptance criteria table.

This output systematically compares each calculated parameter against its corresponding allowable limit based on TEMA and ASME standards. The table uses a clear pass/fail indication for each criterion, offering an immediate overall assessment of design compliance. For the current

Table 3. Acceptance criteria comparing calculated parameters with allowable limits based on TEMA and ASME standards.

Mechanism	Value	Status
Vortex Shedding	0.12	PASS
Turbulent Buffeting	8.7 N	PASS
Fluid Elastic Instability	0.12	PASS
Acoustic Resonance	Axial: 0.04 Angular: 0.00	PASS
Mid-span Collision	0.01 mm	PASS
Tube Wear Damage Thickness	1.2699 mm	PASS
Fatigue Failure	0.0 MPa	PASS
Excessive Noise	34.0 dB	PASS
Pressure Drop	0.00 bar	PASS
Stress Corrosion	0.0 MPa	PASS

case study, all criteria were satisfied, though the tube wear thickness result was noted as being close to the allowable limit. This level of detail supports informed decision-making and prioritization of design improvements where margins are tight.

4. CONCLUSION

This research underscores the critical importance of a comprehensive approach to flow-induced vibration assessment in the design of shell-and-tube heat exchangers. The development and application of the MAK-FIV tool demonstrates that a structured analysis, which accounts for the principal excitation mechanisms, namely fluid-elastic instability, vortex shedding, turbulent buffeting, and acoustic resonance, provides a robust basis for predicting and mitigating potential structural damage. The tool's integrated framework enables a detailed evaluation of how these excitation mechanisms influence specific failure modes, including fretting wear, fatigue, mid-span tube collisions, excessive noise, pressure drop, and the susceptibility to stress corrosion. The findings from the sample case study illustrate the tool's capacity to identify critical parameters, such as natural frequency and critical velocities, and to assess their relationship with operational conditions. This allows for a nuanced understanding of design vulnerabilities that might otherwise remain hidden. By grounding its calculations in widely accepted engineering standards and empirical data, MAK-FIV offers a pragmatic and defensible approach to design verification. It supports engineers in moving beyond simple compliance checks towards a more informed, risk-based design strategy that prioritizes long-term operational safety and reliability. Looking ahead, further refinement of the tool would benefit from incorporating more advanced analytical capabilities.

Future work should focus on integrating multimodal dynamic interactions, which are often present in complex flow fields, as well as extending the framework to handle multiphase flow conditions, which represent a significant challenge in many industrial applications. Experimental validation of the tool's predictions under controlled conditions would also serve to strengthen its reliability. Ultimately, this work contributes to the field by providing a practical, integrated solution for predicting FIV risks, thereby enabling the design of more resilient and durable heat exchanger systems for demanding operational environments.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

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Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the

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Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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