Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 6185-6190

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

THE EFFECT OF VIBRATIONS ON THE TIGHTNESS OF FLANGE JOINTS IN A PIPING SYSTEM

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Abstract

Bolt joints are among the most used mechanical connections across various industrial sectors. Their primary function is not only to join components together but also to ensure tightness under various operational or adverse loads. Therefore, proper design including the determination of the required tightening torque, is essential. In most cases, joint leakage is caused by the loss of bolt pretension. There are various mechanisms for loosening bolt joints. Non-rotational loosening is generally caused by quasi-static/long-term processes. The loss of preload in self-loosening, where the impact and dynamic nature of the load are dominant, occurs when relative motion between the internal thread of the nut and the external thread of the bolt arises. Motivated by concerns about vibration-induced loosening in petrochemical plants, this paper aims to determine effective methods to prevent loosening and ensure joint tightness. This paper presents a detailed computational finite element analysis of an M12 threaded bolt joint subjected to transverse vibration corresponding to the conditions of the Junker's test. The complexity of analyzing a joint's vibration resistance is influenced by a multitude of factors and inputs (e.g. friction coefficients, threads pitches, bolts pretension, etc.), which are discussed. The paper also deals with results comparison to bolt joints having other standardized thread pitches. Furthermore, the study includes evaluation for various friction coefficients between the nut and the washer, corresponding to lubrication between these components. Based on the results of computational analyses combined with analytical insights, conclusions are drawn for the identification of joints where enhancing vibration resistance (loosening prevention) would improve operational safety and reliability.

Keywords: Bolt Joint, Transversal Vibration, Preload Decrease, Self-Loosening, Junker's Test, Piping System.

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doi: 10.7712/120125.12881.25656

1 INTRODUCTION

The motivation for this paper was an incident during unstable operation of a propylene system in the petrochemical plant, which resulted in strong vibrations of the piping system and process equipment. According to the operator, opening the safety valves caused chattering (intense shock oscillations of the moving part of the safety valve), which excited a significant part of the piping system. As a result of this event, the bolts on the connections of the safety valves and adjacent shut-off valves loosened. The degree of loosening varied; in some cases, the nuts were only partially loosened, while in other cases, they were completely loosened. The consequence was a loss of system tightness and a leak of flammable gas into the environment.

Joint tightness is often compromised by a loss of pretension in the bolt joint. Pretension loss has two main causes: 1) non-rotational loosening, where the nut stays fixed, but grip weakens, and 2) rotational loosening (self-loosening), where the nut unscrews.

It is important to note that the mechanisms in these two basic categories are fundamentally different: while quasi-static/long-term processes play a role in non-rotational loosening, the impact and dynamic nature of the load are decisive in self-loosening.

1.1 Non-rotational loosening

While this paper primarily focuses on self-loosening due to transverse vibrations, it's important to note that non-rotational loosening mechanisms can also reduce pretension and increase susceptibility to self-loosening. Factors like initial relaxation of the joint components (including the nut), gasket creep, differential thermal expansion of the joint components, caused by temperature differences and dissimilar materials, and permanent eventually creep deformations can all contribute to pretension loss. However, only joint settlement requires immediate attention, as the other mechanisms are typically accounted for in the design phase.

1.2 Rotational loosening (Self-Loosening)

Junker's research [1] identifies transverse vibrations as the primary cause of bolt loosening in engineering applications, while axial and torsional vibrations are less critical, except in rotating machinery. Junker demonstrated that pretension loosening occurs when relative motion develops between the nut and bolt threads. This motion, facilitated by thread clearance, happens when transverse forces exceed the frictional forces, which depend on pretension and the friction coefficient. Once slipping begins, the friction coefficient drops significantly, leading to a loosening torque. Under cyclic loading, this mechanism can rapidly loosen the joint. To initiate loosening, transverse forces must overcome joint compliance and frictional resistance. Once these forces exceed a critical threshold, thread slip occurs.

Several authors have further explored the mechanisms of self-loosening in bolt joints. Ramey and Jenkins [2] conducted experimental analysis to investigate thread movement in bolt connections subjected to vibrations. Their work provided valuable insights into the dynamic behavior of threaded fasteners under vibrational loading.

Eccles [3] investigated the tribological aspects of self-loosening, examining the influence of friction coefficients, lubrication, and surface conditions on the loosening process. He further explored the loosening characteristics of prevailing torque nuts in [4].

Fernando [5] provided a comprehensive overview of the mechanisms and prevention of self-loosening in bolt joints. He identified several factors contributing to self-loosening, including vibration amplitude and frequency, preload level, and the presence of transverse loading.

Hattori et al. [6] investigated the loosening and sliding behavior of bolt-nut fasteners under transverse loading, highlighting the significance of the load direction and magnitude on the loosening process.

1.3 Techniques for preventing joint loosening

Bolt joint resistance to vibration loosening can be achieved through appropriate design and locking methods. Standardized procedures are often incorporated in the design stage, with VDI 2230 [7] offering comprehensive guidance on all aspects of bolt joint design. Locking mechanisms can be classified into three main categories based on the locking mechanism: increasing friction, geometric locking, and clearance elimination.

Increasing friction in the joint, through methods like spring washers and self-locking nuts, enhances resistance to vibration. However, this approach has limitations in high-vibration environments, as excessive vibration can overcome the frictional force.

Geometric locking utilizes bolts, nuts, and washers with specialized locking teeth. These teeth engage with mating components upon tightening, creating a form-closed joint that effectively captures the loosening torque and prevents vibrational loosening.

Finally, eliminating clearance within the thread directly addresses the mechanism of self-loosening. By preventing any relative movement between the internal and external threads, using adhesives or specialized threads, vibrational loosening is effectively prevented.

2 COMPUTATIONAL ANALYSIS OF BOLT LOOSENING

The goal of the FE analysis was to capture the self-loosening mechanism of bolt joints (i.e., its physical nature) and demonstrate this mechanism under real-world conditions, specifically at the limiting pitch values of commonly used standard threads. The analysis further considered the influence of different friction coefficients between the nut and the washer, accounting for various lubrication conditions.

2.1 Analytical calculation

Initially, a simplified analytical approach for calculating the loosening torque is introduced, drawing upon the work of [3]. The tightening torque T is governed by the equation:

$$T = \frac{F}{2} . \left[\frac{p}{\pi} + \frac{\mu_\mathrm{t} . d_2}{\cos \alpha} + D_\mathrm{e}\, \mu_\mathrm{n} \right] \tag{1}$$

where D_e represents effective nut diameter, T tightening torque, d_2 pitch diameter, p thread pitch, α half thread angle, μ_n and μ_t friction coefficient under the bolt or nut and between threads, respectively.

When transverse slip occurs in the thread, it divides into an ascending and a descending side, resulting in unequal forces on both sides of the thread and producing a loosening moment. Mathematically, this loosening torque can be represented as:

$$\begin{aligned} T_\mathrm{ss} = {} & \int_{r=r_1}^{r=r_2} \int_{\theta=0}^{\theta=\pi} \frac{F}{A_\mathrm{slip}}\, \mathrm{d}A_\mathrm{slip} (\mu_\mathrm{t} \cos \beta + \sin \beta') \cos \beta'\, r \sin \theta \, - \\ & - \int_{r=r_1}^{r=r_2} \int_{\theta=0}^{\theta=\pi} \frac{F}{A_\mathrm{slip}}\, \mathrm{d}A_\mathrm{slip} (\mu_\mathrm{t} \cos \beta - \sin \beta') \cos \beta'\, r \sin \theta \end{aligned} \tag{2}$$

where A_slip represents contact area of the bolt, r_1 and r_2 the inner and outer radius of the circular contact bolt area, respectively.

By modifying equation (2), the total torque acting in the loosening direction under transverse slip conditions can be expressed as:

$$T_\mathrm{loosen} = \frac{Fp}{4\pi} + \frac{Fp}{2\pi} = \frac{3Fp}{4\pi} \tag{3}$$

2.2 Computational model

Simplified models based on the geometry of M12 metric single bolts with standard pitches of 0.75 and 1.75 mm were developed. The computational models represented a connection of two plates using a bolt joint, which consisted of a bolt, two nuts, and washers (Fig.1).

For the dynamic analyses, the following simplifications were made: one side of the joint was modeled with flexible elements (washer, bolt, thread), the remaining components were considered rigid, and the bolt shank was represented as a beam. Frictional contacts (μ = 0.15) were considered in the upper joint between the nut and bolt threads, washer and plate and between the plates. The lower joint connections were assumed fixed.

Initial bolt pretension was set to 10 000 N. Model was fixed at the bottom plate. Upper plate was excited sinusoidally at 10 Hz with 1 mm amplitude for 2 seconds.

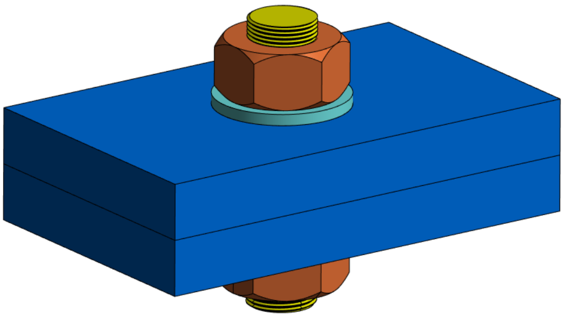

Figure 1: Computational model of an M12 bolt joint.

2.3 Results and discussion

The results of the computational analyses are shown in Fig.2 to Fig.5. Fig.2 represents contact status and stress distribution in the M12 bolt of 1.75 mm pitch thread at maximum displacement during kinematic excitation. When displacement of plate occurs, transverse slip occurs in the thread between the nut and the bolt. This means that conditions for self-loosening of the nut are created in the model (sliding contact status). The results also indicate bolt bending, which influences the distribution of contact pressures as well as the stress distribution within the bolt.

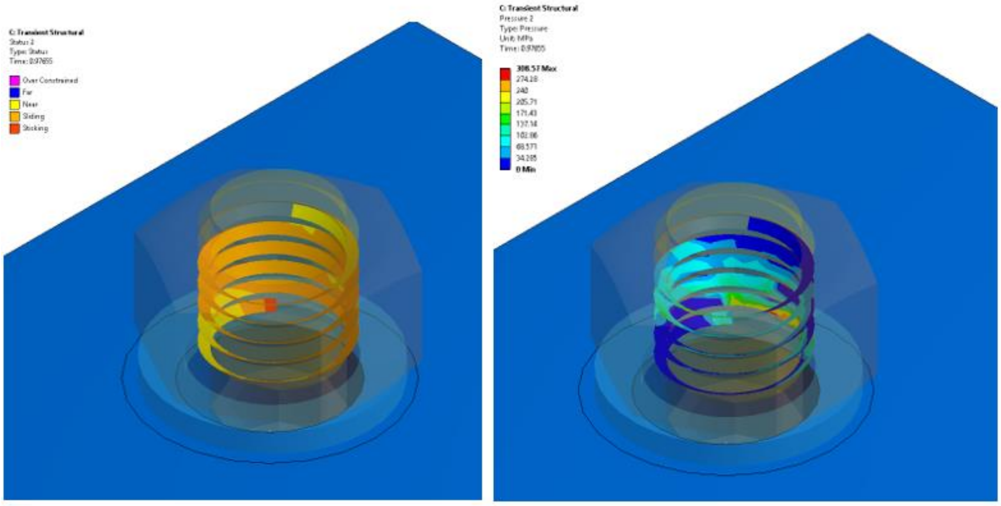

Figure 2: Thread contact status (left) and contact pressure in a bolt (right).

The most important result of the analysis is the time histories of the change in bolt pretension (Fig.3). These time histories clearly illustrate the mechanism of self-loosening: the pretension in the unsecured joint decreases rapidly. The corresponding rotation of the nut is shown in Fig.4. Time-history analyses of M12 bolts with varying standard thread pitches demonstrate an increased susceptibility to self-loosening as thread pitch increases. The higher the thread pitch, the faster the tightening force decreases due to self-loosening.

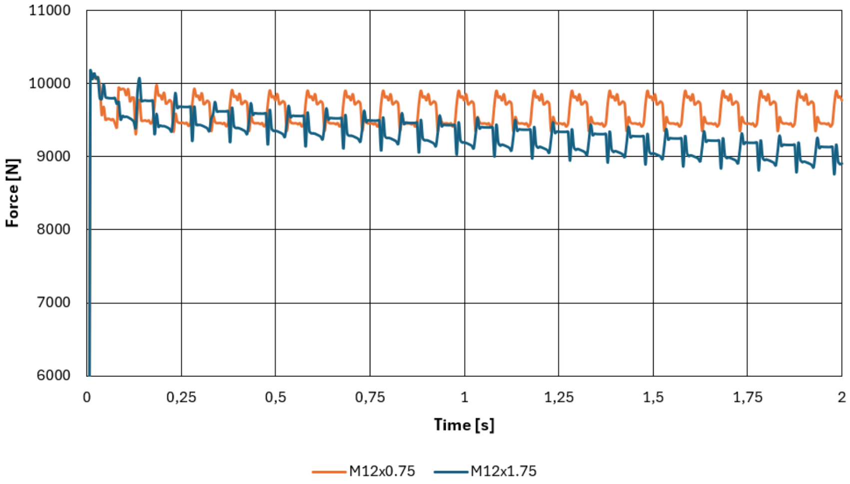

Figure 3: Computed time-dependent pretension in M12 bolts with different standardized thread pitches.

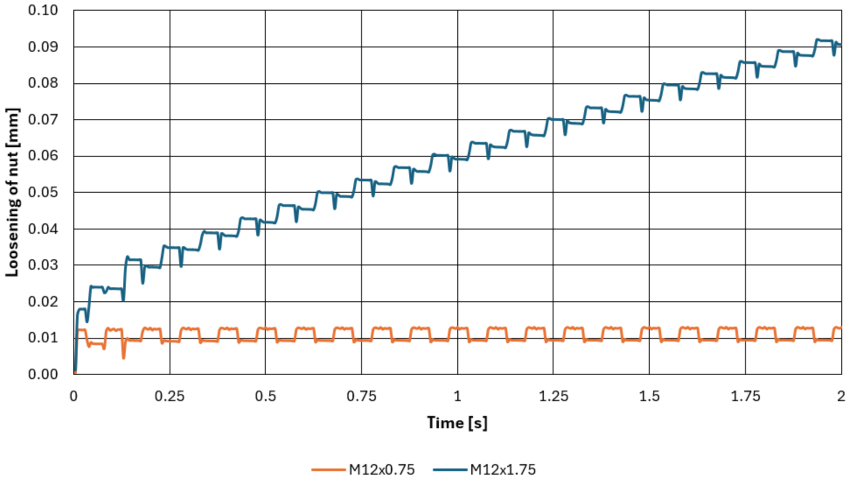

Figure 4: Computed rotation of M12 nuts with different standardized thread pitches over time.

The analysis was modified by considering different friction coefficients between the nut and washer for an M12x1.75 bolt, while maintaining a constant friction coefficient of 0.15 between the bolt threads and nut. Self-loosening of the preloaded bolt joint occurs when relative motion (slippage) occurs between the bolt threads and nut.

Fig.5 shows the time-dependent decrease in tightening force with varying friction coefficients between the nut and washer. With nearly zero friction (representing perfect lubrication), no self-loosening of the nut occurs, as the frictional force generated at this point is insufficient to induce slip in the threads between the nut and bolt. Conversely, as the friction coefficient increases, higher frictional forces are generated, overcoming the frictional forces between the nut and bolt threads and thus causing them to slip relative to each other. Furthermore, the higher the friction coefficient, the greater the decrease in bolt pretension.

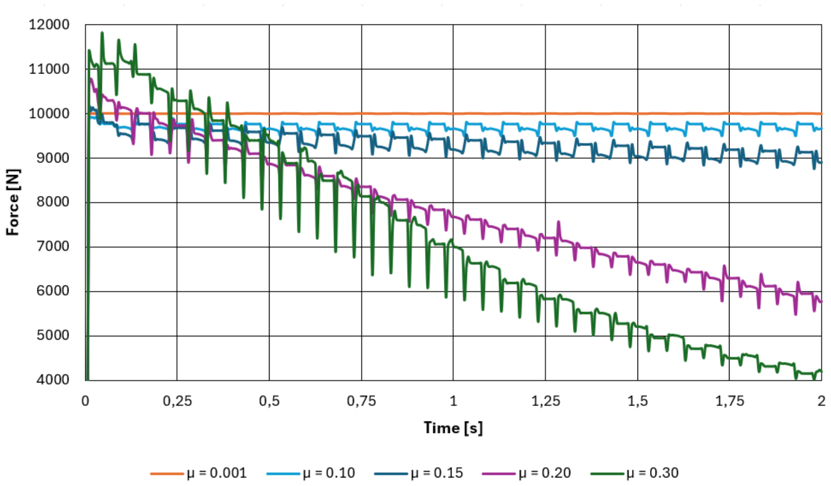

Figure 5: Time-dependent pretension loss in M12x1.75 bolt for different friction coefficients (nut-washer).

3 CONCLUSIONS

This paper focused on self-rotational loosening of bolt joints in piping systems. The results of the numerical analyses performed on an M12 bolt joint confirmed that in the absence of slippage in the threads, no self-loosening occurs. If the entire process is governed by friction, there is always a threshold excitation force that can overcome these frictional forces and loosen the joint. These analyses considered analytical approaches to the problem.

To ensure safe operation of piping systems, design should incorporate various joint securing methods discussed in this paper, including the use of specialized washers to establish a form-closed joint or the elimination of thread clearance.

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