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Parametric Vibration Characteristics Extraction of a High-Power Turbo-Generator Anchor Bolt Utilizing Analytical and Finite Element Methods

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Abstract

In this paper the vibrational behavior of a turbo-generator (TG) anchor bolt is investigated, and its natural frequencies and mode shapes are evaluated by means of two different solution approaches including analytical and finite element (FE) methods. Firstly, the FE solution implemented, and then according to mode shapes, an appropriate boundary condition selected and applied in theoretical solution, and the results of two techniques are compared together. The modal FE analysis is implemented as pre-stress modal approach; because the modal eigenvalues are affected of axial stress resulted by tightening the anchor bolt. In this approach, prime a strength analysis is executed, and all connections, loads, boundary conditions, etc. are considered as their reality. Mesh controls and the other settings are applied properly, to reach the best run time and reliable results. In modal analysis, pre-process settings remained the same, and the contact status, and stress resultants are imported from strength analysis. In analytical method, governing equation is yielded based on Euler-Bernoulli beam theory. Then the natural frequencies, and mode shapes are extracted and explicated. Keeping a safe frequency margin from the excitation force, prevents from any oscillations when the device is running. In this study after vibrational analysis, the effective parameters are introduced, and sensitivity analyses versus important parameters are checked.

Keywords: turbo-generator; anchor bolt; finite element; analytical method; modal analysis.

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1. Introduction

A TG is a vital machine in power plants that converts thermal energy into electrical energy by coupling with a steam or gas turbine. Each TG consists of two main parts: a stationary stator and a rotating rotor. These generators produce very high electric currents linked to input power delivered as high external torque, which transfers to the stator through rotor-stator electrical interaction. Under fault conditions, torque can rise to ten times the rated value, making safety and structural integrity across all operating modes crucial. A major focus is the failure behavior of anchor bolts embedded in concrete foundations—widely used in power plants and precast sectors. Their importance comes from frequent usage, complex failure modes, and difficulty in determining peak strength [1]. Pull-out tests are commonly used as a non-destructive method to evaluate concrete strength onsite [2]. Various supports and reinforcements like rock bolts, shotcrete, steel beams, and wire mesh endure repeated, time-dependent loads from sources such as cyclic blasting in mining, rotor unbalance forces, and excavation stresses [3]. Tizani et al. studied the fatigue behavior of the Extended Hollo-bolt (EHB), showing increased concrete strength enhances fatigue life, with bolt shank fracture as the main failure mode [4]. Another study applied FE and experimental analyses to assess modal behavior in medium-power TG stator components in rated state [5]. Choi et al. investigated subway rail fastening failures, attributing issues to insufficient fastening strength, leading to base plate deformation and shear stress increases; field tests and simulations yielded improved fastening methods [6].

An engineering project examined a TG foundation operating well up to 100 MW but showing excessive vibrations beyond that; the foundation met design standards and vibration limits at rated power [7]. Liu et al. explored resin-anchored supports in deep roadways under high temperature and pressure, identifying failure stages at bolt-resin interfaces and showing stronger rock improves anchoring, while higher temperatures reduce load capacity [8]. Another study linked transverse vibration frequency changes to debonding failures in resin-anchored bolts, creating damage metrics for early warning through dynamic testing [9]. Wang et al. tested Negative Poisson's Ratio (NPR) bolt-anchored specimens under blasting loads, finding NPR bolts increase strength, change failure modes, and reduce rock deformation [10]. ASCE 136 [11] requires turbo-generator foundations and anchor bolts to safely transfer static and dynamic loads. It emphasizes proper bolt embedment, alignment, and foundation stiffness, discourages hooked bolts, and highlights coordination among designers and contractors to prevent vibration, misalignment, and structural or operational failures. Additional research covered foundation structural analysis, dynamic behavior of preloaded shafts/beams, and vibration under axial loads [12–16]. Secure clamping and restraint of rotating equipment, especially high-power electrical machines like TGs, is essential to prevent movement or failure under both rated and fault loads. Effective design includes anchoring systems, chassis, foundations, and provisions for maintenance. Anchor bolts are commonly installed using either post-installed or cast-in methods; this study uses the cast-in approach. The anchoring process involves three key steps: first, determining the number and specifications of anchor bolts based on the worst-case load conditions at the installation site; second, ensuring the site is clean and bolts are correctly positioned; and third, applying the proper tightening torque with correctly engaged threads. Anchor bolt failures typically occur due to five main reasons: overloading, improper installation, corrosion, fatigue from repetitive loading, and hydrogen embrittlement. Fatigue can result from constant vibration caused by excitation forces, potentially leading to failure over time. Since the TG rotor rotates at 3000 rpm, its unbalance force affects all components, making it critical to monitor natural frequencies of TG parts—especially anchor bolts—to avoid resonance with the 50 Hz excitation frequency. A safety margin of 20% between natural and excitation frequencies is recommended.

This study investigates the modal characteristics of turbo-generator (TG) anchor bolts using both analytical and finite element approaches. A coupled analytical–FE framework is developed and validated for the pre-stressed modal analysis of TG anchor bolts. The effects of key design parameters are systematically examined, and their sensitivity on the dynamic behavior of the system is quantitatively evaluated.

2. Modal analysis

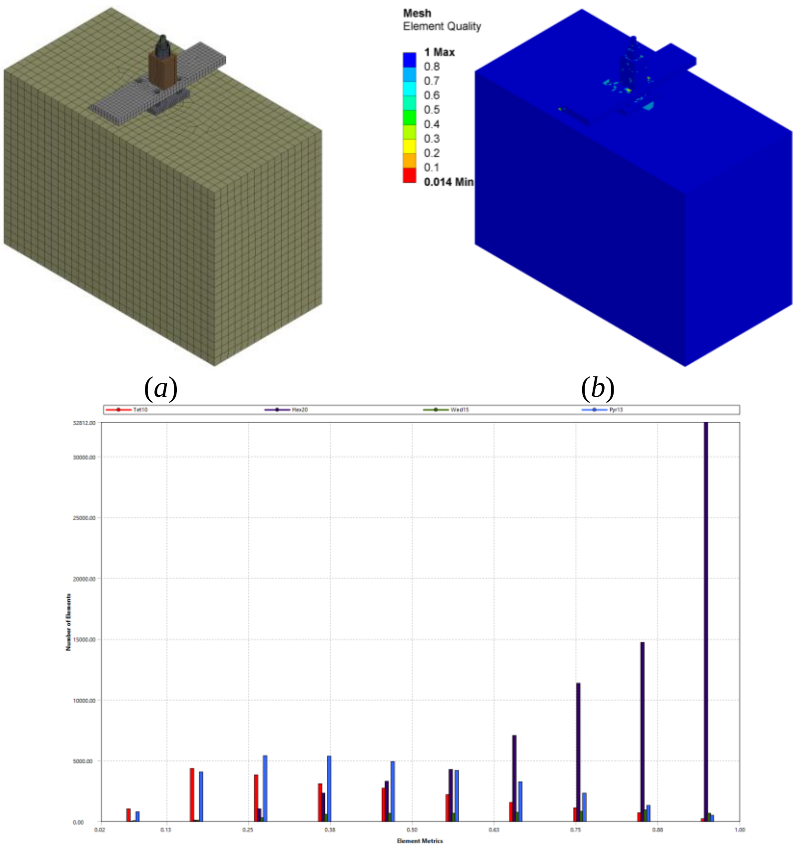
In this section, two methods—analytical and finite element (FE)—are established for investigating the modal behaviour of anchor bolts. Firstly, FE method is applied and after the results assessment, an appropriate boundary condition is selected to be applied in analytical method.

2.1 FE method

The finite element (FE) solution method conducted in this study includes four main steps. First, the geometry was simplified while preserving its original structure (for example the fillets, chamfers were removed, small holes were filled, etc.), and materials were assigned to each component based on properties obtained from destructive tensile tests (see Table 1). Second, connections between components were defined as bonded or frictional contacts according to their nature (e.g., the contact between the nut and bolt defined as frictional-bolt thread, the contact in the interface of fastened components applied as frictional, and the welded bodies considered in bonded mode). For the welded parts, the contacts formulated by Multi-Point Constraint (MPC) and symmetrical contact behavior applied for equal connections. Third, mesh settings—including element order, size, and method—were carefully configured to ensure model accuracy, using very fine brick elements with quality scores mostly above 0.8 (maximum 1), as shown in figure 1. Finally, boundary conditions and mechanical loads were applied, with a symmetry plane set on the foundation's outer face and a mechanical load resulted by tightening torque (it was applied by means of bolt pretension feature). These boundary conditions and loads are illustrated in figure 2.

Table 1. Mechanical properties of materials

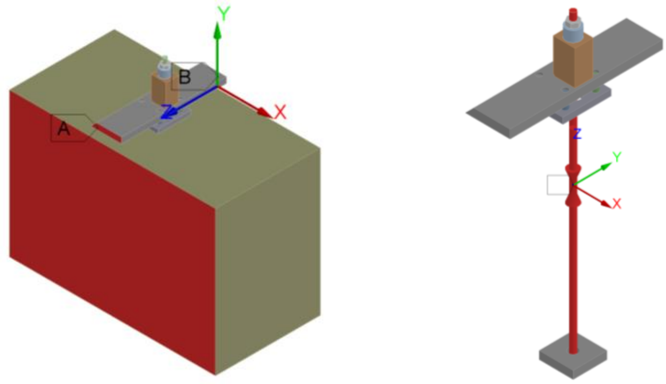
No.	Property / Material	ρ (kg/m³)	E (GPa)	υ	S_y (MPa)	S_{ut} (MPa)	El. (%)
1.	Steel Mat. 1	7800	200	0.3	685	980	13
2.	Steel Mat. 2	7800	200	0.3	550	770	16
3.	Steel Mat. 3	7800	200	0.3	650	1000	12
4.	Foundation	2300	30	0.18	-	42	2



(*a*) (*b*)

(*c*)

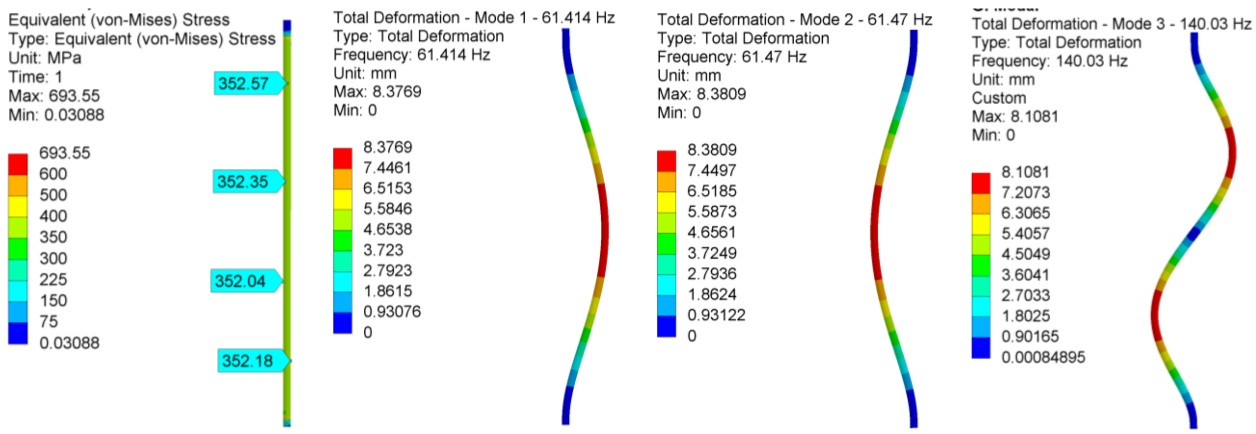
Figure 1. *a*) Meshed geometry for simplified model, *b*) Element quality graph, *c*) Element scatter diagram along with the distribution and accumulation of different quality levels.



(*a*) (*b*)

Figure 2. *a*) Symmetry boundary condition in symmetrical surfaces, *b*) Anchor bolt pretension load superimposition.

When the pre-process steps were completed, simulation was implemented as pre-stress modal according to its reality. In the post-process stage, results were extracted and presented in figure 3.



(*a*) (*b*) (*c*) (*d*)

Figure 3. Main anchor bolt result contours *a*) Stress distribution, *b, c*) Fundamental frequencies in x-y, and z-y planes, and *d*) Second frequency, mode shapes.

Figure 3 shows the anchor bolt with other elements hidden for clarity. Pretension produces a von-Mises stress of 352 MPa along the bolt. The measured natural frequencies are 61.4 Hz, and 140 Hz, with higher modes far from the 50 Hz excitation frequency. The first two frequencies (fundamental frequencies) are above 60 Hz, and are in admissible frequency range. Since the tightening torque results high stress values (especially in thread region), it necessitates high grade materials for anchor bolt fabrication.

2.2 Analytical method

To solve problems in continuous media, the equilibrium equation matching the problem's physics must be addressed. When the medium lacks geometric or material complexities, or when simplifications preserve essential conditions, analytical solutions are effective. Unlike numerical methods such as Finite Element Method (FEM) or Finite Difference Method (FDM), analytical approaches offer higher accuracy and faster solutions. In this study, because the anchor bolts have simple geometry and uniform material properties, an analytical method is suitable for accurately determining their vibration response.

2.2.1 Frequency analysis of the beam–column

In the initial phase, the vibration equation for a beam-column (which is a beam that can support both transverse and axial loads) with a straightforward cross-section is formulated for a differential element, utilizing the Euler–Bernoulli beam theory. This derivation employs Newton's method and treats the inertia force as an external force. By disregarding higher-order differential terms and executing suitable algebraic simplifications, the equation's final form can be presented in the form of (1) formula [15]:

$$\frac{\partial^2}{\partial x^2}(EI\frac{\partial^2 w}{\partial x^2})+\rho A\frac{\partial^2 w}{\partial t^2}-P\frac{\partial^2 w}{\partial x^2}=f(x,t) \tag{1}$$

Where w, E, I, ρ, A, P, and $f(x,t)$ are the representatives of vibration response, young's modulus, moment inertia, density, surface area, pretension load, and external excitation force, respectively. Using the variables separation method in the form of $w(x,t)$=W(x)T(t), the answer can be expressed as follows:

$$W(x)=c_1\cosh s_1x+c_2\sinh s_1x+c_3\cos s_2x+c_4\sin s_2x \tag{2}$$

$$w(x,t)=(c_1\cosh s_1x+c_2\sinh s_1x+c_3\cos s_2x+c_4\sin s_2x)(A\sin\omega t+B\cos\omega t) \tag{3}$$

$$s_1=\sqrt{\frac{P}{2EI}+\frac{1}{2}\sqrt{(\frac{P}{2EI})^2+\frac{4\rho A\omega^2}{EI}}}\ ,\quad s_2=\sqrt{\frac{1}{2}\sqrt{(\frac{P}{2EI})^2+\frac{4\rho A\omega^2}{EI}}-\frac{P}{2EI}} \tag{4}$$

The mode shape (equation (2)) incorporates constants that are established through the application of suitable boundary conditions. Drawing from the insights acquired through finite element analysis and the examination of deformation at both the initial and terminal sections of the anchor bolt, it is justifiable to presume clamped–clamped boundary conditions at both ends (results given in Figs. 3-(b), (c), and (d) shows no angle in clamping points, and confirms the mentioned claim). Given these boundary conditions, the constraints on deformations can be articulated as follows:

$$W(0)=0\ ,\quad \frac{\mathrm{dW}}{dx}(0)=0\ ,\quad W(l)=0\ ,\quad \frac{\mathrm{dW}}{dx}(l)=0 \tag{5}$$

Inserting the boundary conditions (5) into equation (2), one derives the set of equations (6):

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ \cosh s_1l & \sinh s_1l & \cos s_2l & \sin s_2l \\ 0 & s_1 & 0 & s_2 \\ s_1\sinh s_1l & s_1\cosh s_1l & -s_2\sin s_2l & s_2\cos s_2l \end{bmatrix}\begin{Bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{6}$$

In order to achieve a non-trivial answer, the coefficient matrix determinant associated with the unknown variables shall be equated to zero.

$$\begin{aligned} &s_1s_2\sinh(s_1l)^2-s_1s_2\cosh(s_1l)^2-s_1s_2\sin(s_2l)^2-s_1s_2\cos(s_2l)^2 \\ &-s_1^2\sin(s_2l)\sinh(s_1l)+s_2^2\sin(s_2l)\sinh(s_1l)+2s_1s_2\cos(s_2l)\cosh(s_1l)=0 \end{aligned} \tag{7}$$

2.2.2 Anchor bolt frequency analysis eigen values

Using the established pretension force and beam–column parameters, the natural frequencies of the structure can be determined. Since Equation (7) lacks a closed-form solution, it is solved numerically. This study calculated natural frequencies for various pretension values, as shown in table 2 (with corresponding mode shapes indicated in figure 4), where n/2 represents the lateral half-wave number. When a 500 kN pre-tension is superimposed on the anchor bolt, first and second natural frequencies are calculated as 58.5 Hz, and 137.9 Hz, through analytical method, and when FE method was adopted, those evaluated as 57.24 Hz, and 133.1 Hz, respectively. There are under 4 percents deviations between the analytical and FE method results, and it can be neglected.

Table 2. The trend of frequency yielded from (7) equation solution against tension bolt pretension

n/2	f (Hz)					
	F_p=1000 kN	F_p=2000 kN	F_p=4000 kN	F_p=8000 kN	F_p=16000 kN	F_p=30000 kN
1	69.93	94.02	127.44	174.84	245.17	335.31
2	145.7	174.84	221.25	308.68	424.16	595.77
3	239.04	277.23	346.93	461.16	636.74	850.4
4	412.63	475.58	531.08	665.25	860.35	1124.35
5	590.29	684.32	731.33	903.72	1159.69	1440.21

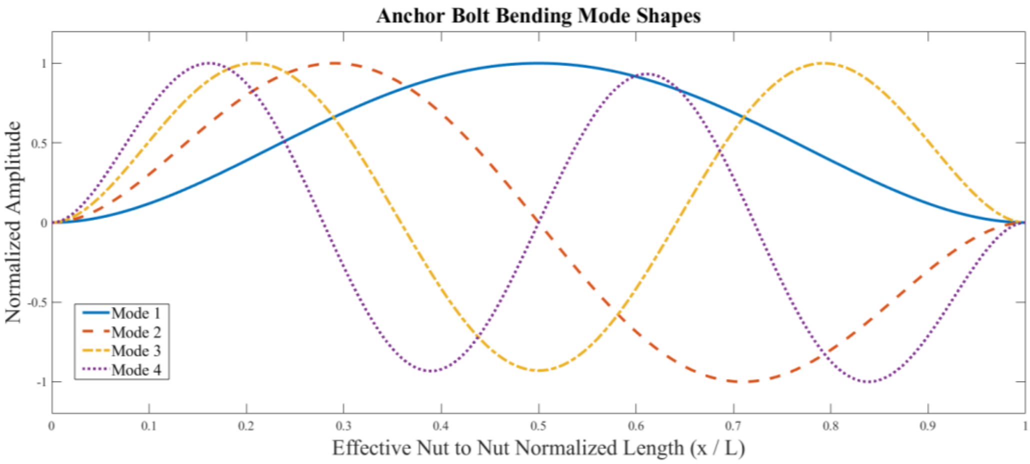
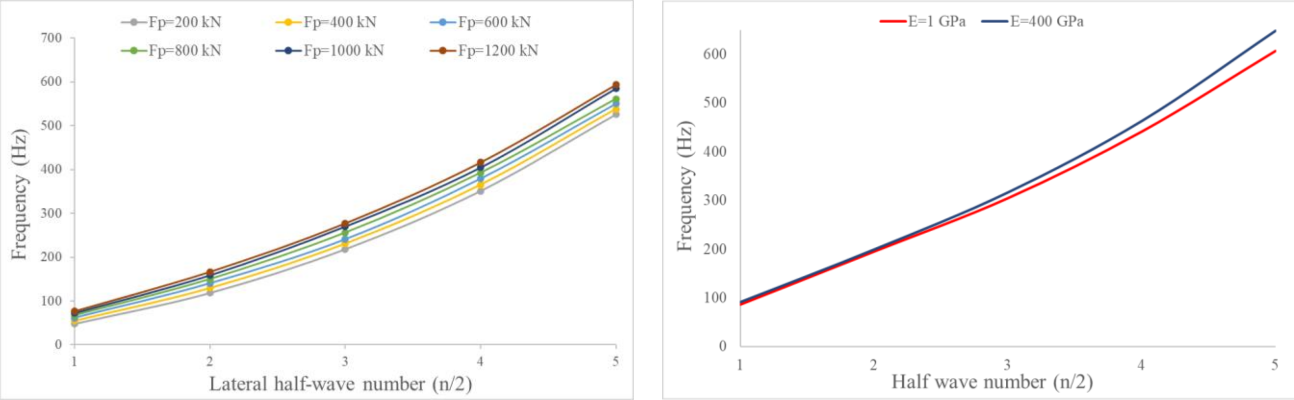


Figure 4. Anchor bolt normalized bending mode shapes achieved through analytical solution method

3. Sensitivity analysis

This section investigates how input parameters affect the natural frequencies of an anchor bolt under different boundary conditions and pre-tension forces (figure 5). Due to the complexity and time required to analyze all mode shapes, the focus is on the five transverse vibration modes of the bolt. Results show that increasing the pre-tension force raises the bolt's natural frequency, especially in higher vibration modes. A key relationship exists between the anchor bolt and the surrounding concrete, where displacements under the bolt head align with those of the adjacent concrete, particularly in the pressure cone area, during both loading and unloading. The Young's modulus of the concrete, representing its stiffness, directly influences the bolt's frequency; higher concrete stiffness leads to increased system stiffness and frequency changes that may be linear or nonlinear. If pre-tension is held constant, reducing concrete stiffness causes more bolt elongation. Comparing beams under equal tensile forces shows shorter beams have higher vibration frequencies. Therefore, increasing the foundation's Young's modulus is expected to decrease the anchor bolt's natural frequency, as demonstrated in the study's results.



(*a*) (*b*)

Figure 5. *a*) Variation of the main generator anchor bolt frequency under different pre-tension values, *b*) Variation of the main anchor bolt frequency under a constant specific pre-tension and different foundation Young's modulus values.

Analysis reveals frequencies rise with higher Young's modulus, especially at higher wave counts, contradicting earlier assumptions. A stiffer foundation causes the anchor bolt boundary to act more like a clamped support, while lower modulus resembles a free support. It is obvious that natural frequencies are affected of system stiffness; in other words when the system be stiffer, natural frequencies increases. In figure 6, the variations of the anchor bolt natural frequencies are illustrated for different boundary conditions. Since in free-free boundary conditions it is not available to apply any pre-tension on the anchor bolt, here in this figure a comparison is done for simply supported and clamped types.

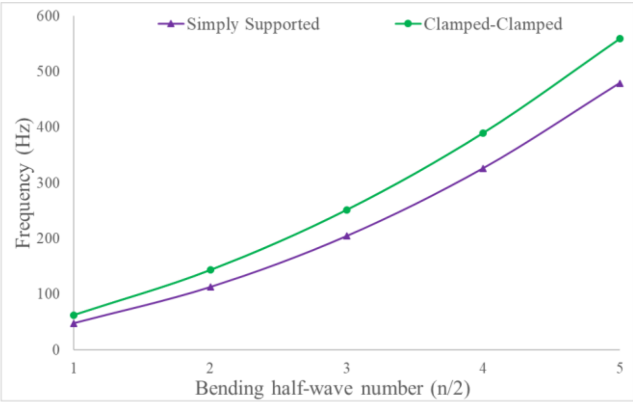


Figure 6. Variation of the anchor bolt frequency under an appointed pre-load versus different boundary conditions

Conclusion

This study investigated the vibration characteristics of a turbogenerator anchor bolt using both analytical and finite element methods. The finite element analysis, included pre-stressed modal analysis and identification of relevant boundary conditions. Results from both methods were compared. Finally, a sensitivity analysis was conducted to assess the impact of different factors on the system's vibration behavior.

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