School of Information Technology and
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at the George Washington University

DIAGNOSIS OF FOUNDATIONS OF 220-500 KV AERIAL ELECTRICAL TRANSMISSION LINE SUPPORTS

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(Shamkhal Abilov)

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THESIS ACCEPTANCE

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ABSTRACT

This thesis explores a vibration-based diagnostic method for assessing foundation condition in 220-500 kV overhead electric transmission towers. Research evaluates model for the mass-spring-damper system for a transmission tower and its foundation, with realistic values for its mechanical properties obtained from literature studies, coupled with information from the Aghsu 220kV Corridor. Simulation studies are conducted dynamically, with soil properties being varied for different forces, simulating operational forces like wind excitation. Outputs simulated for transient response to these forces include displacement, velocity, and acceleration, processed with filtering algorithms, Fast Fourier Transforms, spectral analysis, and features extracted for diagnostic indicators like frequency deviations, damping ratios, and acceleration magnitude levels, in combination forming a diagnostic foundation to ascertain differences between a healthy foundation from a deteriorated foundation.

Simulation results are validated with model predictions based on operational expectations, along with published values from international studies. The simulation results for natural frequency (≈2-12 Hz) and damping coefficients (0.03-0.08) for modelled soil-structure interaction dynamics match published values from observed practices in the energy sector. It has now been validated from simulation analysis that vibration diagnostics have proved to be an efficient, non-destructive technique for condition analysis to monitor Azerbaijan's 220-500 kV high-voltage transmission network. The thesis explores a vibration diagnostic technique to analyze the condition of foundations for 220-500 kV overhead electrical transmission towers. Conventional visual analysis, adopted in Azerbaijan's energy power network, explored on-site defects, such as deviations in overhead wires, gaps in support foundations, with no information regarding changes in soil resistance for support foundations. By overcoming these defects, researchers developed simulation-based analysis on mathematical models for dynamic soil-structure interaction principles to explore early indicators for loss, degradation, and damage to electrical support foundations. Starting with creating simplified mass-spring-damper models for the transmission tower, along with its foundation, based on real-world, realistic model parameters extracted from literature, in addition to simulation analogues for the Aghsu 220 kV route, dynamic simulations with varying soil properties for different levels of stiffness, damping, and forces are employed for simulating operational forces such as wind-borne vibrations. Along with simulation results on displacement, velocity, and acceleration, post-processing is performed on these parameters for filtering, spectral analysis based on Fast Fourier Transforms, and indications such as natural frequency deviations, damping ratios, and Root Mean Square acceleration indicators. Outputs from the model are validated by comparison with analytical results and published values in international studies. The match between model results for natural frequency ranging between 2-12 Hz, with damping coefficients between 0.03-0.08, is accurate enough to validate model performance in simulating real-life dynamic performance for transmissions in real foundations. These results validate the utilization of vibration analysis for diagnosing real foundations, particularly for identifying loss in foundation stiffness, which will not be detected during conventional analysis. Concluding, this method is an efficient, non-destructive, and scalable process for testing Azerbaijan's high-voltage power transmissions, with applications for incorporating automated analysis via machine learning algorithms in its evaluation method.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
AC	Alternating Current
DAQ	Data Acquisition
DC	Direct Current
FFT	Fast Fourier Transform
FEA	Finite Element Analysis
FHI	Foundation Health Index
SF	Sampling Frequency
GPR	Ground Penetrating Radar
IE	Impact-Echo
IR	Infrared Thermography
MDOF	Multi Degree of Freedom
SDOF	Single Degree of Freedom
NDT	Non-Destructive Testing
PPE	Personal Protective Equipment
PSD	Power Spectral Density
RC	Reinforced Concrete
RMS	Root Mean Square
RMSE	Root Mean Square Error
SHM	Structural Health Monitoring
SSI	Soil–Structure Interaction
TDA	Transboundary Diagnostic Analysis
UPV	Ultrasonic Pulse Velocity

CHAPTER ONE

INTRODUCTION

The reliability and stability of modern power systems directly depend on the mechanical and structural condition of transmission lines. In particular, the foundations of overhead power transmission line support with a voltage of 220–500 kV are one of the most important elements of energy infrastructure. These foundations both ensure the stability of the support and evenly distribute external influences such as wind, icing and seismic loads through the soil. Traditional technical inspection methods, including visual inspections and periodic tests, in many cases do not allow for timely detection of hidden damage to the foundations or mechanical weakening between the soil and the foundation. As a result, this can lead to sudden structural deformations, power outages and safety risks. While it is true that this process can identify defects on the surface, it does not provide sufficient information for any underlying defects that may arise beneath the surface. Physical inspections also entail traversing the huge territories covered by the transmission corridors.

Recently, the use of advanced sensing and data analysis for diagnosing the strength of structures has attracted considerable interest, and it has been founded on the belief that it could provide an efficient methodology for diagnosing the health of structures. Among the promising methods for diagnosing subsurface damage, without any excavation, is the use of vibrations. Analyzing the dynamic behavior of the corresponding system formed by the structure and the foundation will enable detection and association of anomalies that could indicate damage to the foundation, an element that supports the structure. The increasing digitalization process occurring in Azerbaijan's energy sector makes it possible to use advanced analysis software.

The presented research aims to apply and improve a vibrational diagnosing methodology to assess the state of the foundations for the 220–500 kV transmission towers, using modeling and simulation in MATLAB-Simulink, setting specific parameters corresponding to local power line structures, for example, in the Aghsu 220 kV line. The goal is proving that it is possible to monitor in a cost-efficient, continuous, and accurate way, using vibrations instead of traditional methods, thereby making a contribution towards ensuring safe and sustainable maintenance for the power system in Azerbaijan.

PROBLEM STATEMENT

The reliability and stability of high-voltage transmission lines are highly reliant upon the actual condition of the foundation structures. For Azerbaijan's electrical energy system, in numerous regions, particularly for 220 kV and 500 kV electrical energy transmission corridors, a considerable number of foundation structures have remained in operation for several decades, thereby facing continuously varying dynamic loads and environmental factors. The process of settlement, reinforcement corrosion, water seepage, and dynamic loads from either wind or seismic forces cause the foundation structure's stiffness to decrease without any apparent indication on the surface.

Despite such hazards, the prevailing methods for inspections in most utility outfits, including Azerenerji

OJSC, remains largely dependent on simple ways. The application of a vibration analysis system will enable the determination of a continuous, unbiased indication related to the foundation health status at any time for the foundations that support the transmission towers. However, there is a lack of similar studies related to similar conditions prevailing in Azerbaijan.

DEFINITION OF TERMS

To avoid confusion, important definitions for terms used throughout this study will be defined for clarity's sake:

- Transmission Tower Foundation: This is the reinforced concrete foundation that holds a transmission tower in place and transfers its loads to the soil.
- Vibration Based Diagnosis: Non-destructive systems health related to translational motion vibrations, wherein dynamic system responses (acceleration, velocity, displacement) are analyzed for an externally/ambiently induced system.
- Damping Ratio: A dimensionless parameter representing energy loss in a vibrating system; it indicates how quickly vibrations decay after excitation.
- Stiffness (k): The modulus that reflects the relationship of applied pressure to displacement, used for foundation rigidity measurement.

- Data Acquisition (DAQ) System: An electronics system used to digitize signals from sensors, such as accelerometers or geophones, to analyze them using software packages, for example, MATLAB.

SIGNIFICANCE OF THE STUDY

The proposed research can also form a basis for creating a framework for using vibrations for diagnosing the foundations of transmission towers for the high-voltage electricity grid in Azerbaijan. The combination of modeling efforts and simulations using MATLAB and Simulink software can also enable the use of dynamic characteristics, for example, stiffness and damping, to diagnose any hidden problems in the foundations. The proposed research can allow Azerenerji OJSC for example, to use more efficient methods for diagnosing the foundations, cut down on costs associated with diagnosing, and avoid any unforeseen breakdowns in the structures.

LIMITATIONS OF THE STUDY

Although the work above offers a comprehensive solution to the problem of transmission tower foundation diagnosis via vibration analysis, there are some limitations that should be noted. The simulations and analysis were carried out based on model parameters that include data from the Aghsu 220 kV transmission line. This work lacks comprehensive experimental testing on a larger scale. The findings of the work above offer important information that can be used as a starting point for further investigations on testing the accuracy of the proposed solution.

CHAPTER TWO

REVIEW OF THE LITERATURE

The chapter is organized thematically to progress from general principles of engineering to more specific diagnostic methods. Section 1 reviews typical foundation types and associated structural behaviors. Section 2 discusses geotechnical and environmental risks that can jeopardize foundation integrity. Section 3 unifies relevant case studies and delineates current knowledge gaps within an Azerbaijan setting context. This thematic structure is intended to provide technical fundamentals as well as localized information to provide a foundation for further development of the diagnostic method in following chapters of the thesis.

2.1. Foundation types used in Transmission Towers for HV Uses

Foundation structures bear the structural frame necessary for high voltage transmission towers, lifting them in such a manner as to transfer vertical and horizontal superstructure loads into the ground. Foundation system performance and selection become the dominant factor in the attainment of both the long-time stability and reliability in transmission facilities, especially in geographically diverse environments such as Azerbaijan, where variability in soil conditions, earthquake characteristics, and water table conditions make foundation performance an issue. This section reviews the main types of foundations employed in 220–500 kV transmission line towers, focusing on pad, pile, and grillage foundations—the most prevalent systems worldwide.

2.1.1 Pad (Spread Footing) Foundations

Pad foundations or spread footings are shallow foundations used fairly often when the bearing capacity of the soil is suitable. The depth of pad foundations usually ranges from 1.5 to 3 meters but can be varied based on the depth of the frost line and geotechnical site profiles [1]. They are quite cheap and easy to construct and suit level land and shallow water tables and low erosion conditions. They cannot be used in soft ground or areas of high seismic hazard in which uplift on foundations and differential settlement become issues.

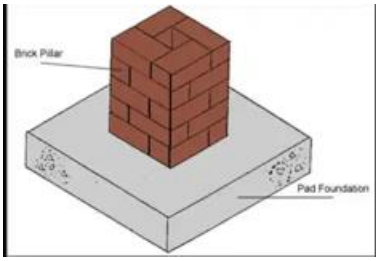


Figure 2.1. Pad type Foundation

2.1.2 Pile Foundations

Pile foundations are deep foundations used for transmitting loads into stronger layers of soil or rocks at greater depths. They are used on weak or compressible surface soils. Transmission towers at riverbanks or floodplains or wetland areas generally rely on pile foundations due to the limited load capacity of upper soils in those areas [2].

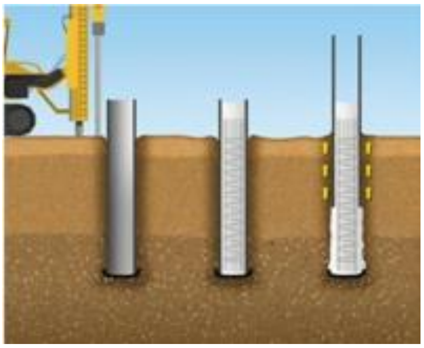


Figure 2.2. Pile Type Foundation

2.1.3 Grillage Foundations

A grillage foundation consists of an orthogonal composition into beams or an orthogonal layer in the form of reinforced concrete or steel beams in the structural plan. It facilitates load transfer from towers through the large area of soil, where in rocky soil and sloping soils, it may be impossible or become economically undesirable [3]. It is commonly used in angle towers, dead-end towers, or in buildings under high lateral loads. The steel elements of the grillage systems are usually galvanized for anti-corrosion, and precast elements in some systems are incorporated in an attempt to obtain the most efficient process in the building process. Even though grillage foundations perform well in supporting towers under complicated loading conditions, careful fabrication and installation process is necessary, leading towards high construction costs.

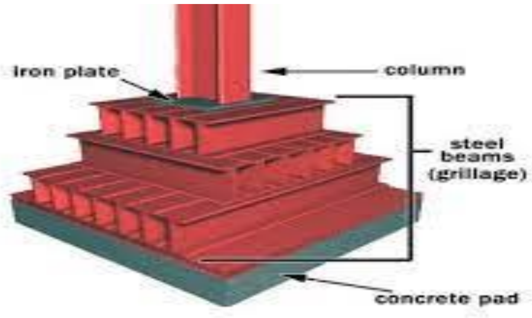


Figure 2.3. Grillage type foundation

2.1.4 Comparative analyses and the selection criteria

The choice of the right foundation type depends on many criteria such as structural load requirements, geotechnical characteristics, environmental constraints, and cost considerations [4]. As an example, grillage and piling foundations might perform better in cases with dynamic loads or conditions in soft soil; however, the same require higher investment in finances and advanced technical skills. In contrast, pad foundations can be used in typical tower structures on solid soil; however, their effectiveness might be compromised in areas prone to settlement or uplift. In Azerbaijan, local conditions including seismicity, the level of the water table, and soil inhomogeneity require the choice in each case of foundations. Recent local energy supplier surveys like that of Azerenerji showed the trend towards hybrid foundation systems consisting of both surface and deep elements for achieving the best cost and performance in different parts of the country.

2.2 Load Transfer and Structural Behavior of Transmission Tower Foundations

The structural response in the base of the transmission towers is largely governed by the mechanism in which vertical, lateral, and uplift loads are transferred to the supporting soil or the strata of the rocks. Due to the nature that high-voltage towers experience difficult static and dynamic loadings like wind, conductor tension, and seismic loading, the foundations need to be able to resist the loads and distribute them efficiently, besides ensuring structural stability during the application duration [5].

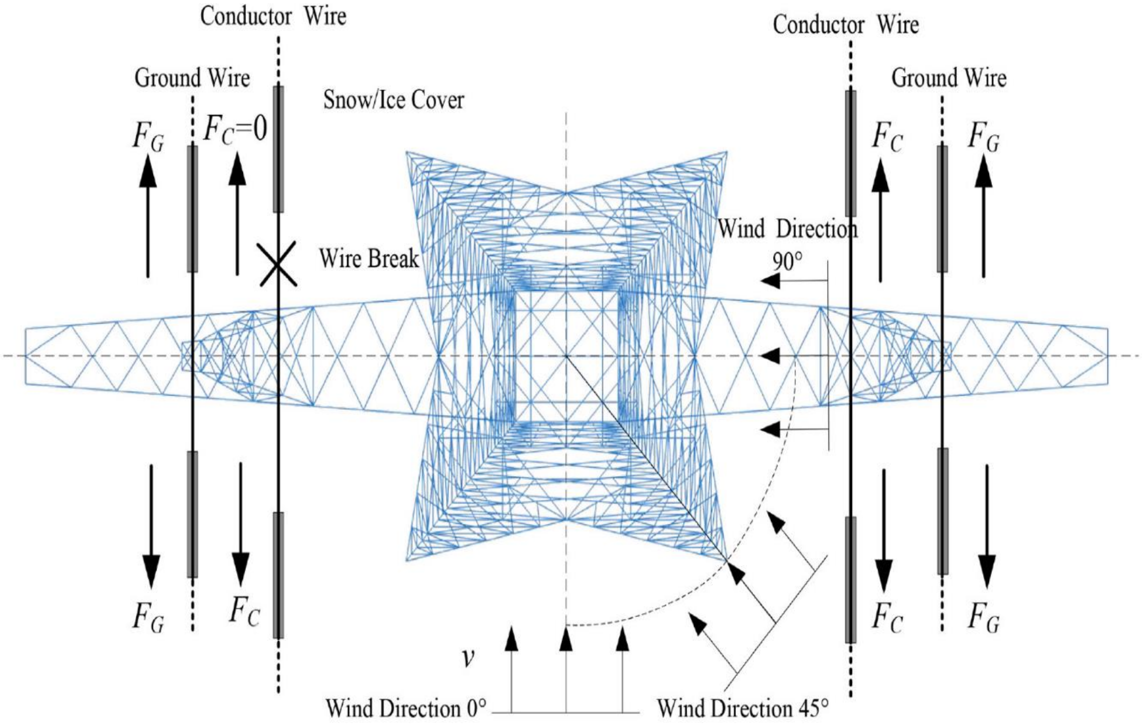


Figure 2.4. Applied loads on the transmission tower structure.

2.2.1 Load Transfer Mechanism

The load transfer mechanism of the foundation depends mainly on the type, geometry, and soil interaction of the foundation. Foundation types, in general, need to contend with three major categories of loads:

- Axial (vertical) loads comprising the weight of the equipment it supports and the tower.
- Lateral loads due to wind, conductor tension, and earthquakes,
- Mitigate loads caused by unbalanced tension in conductors, especially in suspension or angle towers.

Vertical loads are transferred directly into the ground through bearing pressure in the pads, while weight along with passive soil pressure acts against the lateral forces. Such shallow foundations, however, are exposed to overturning and sliding in the case of low soil strength or high lateral loads [6].

While the piles transfer loads through end bearing at the pile base and skin friction along the pile, the group piles resist loads through horizontal soil mobilization and bending of the units in the piles. Modern analysis prefers p-y curve modeling in the simulation of the response of piles and soil to lateral load [7].

The grillage foundation beam structures affect each other, differing in the manner in which they perform. There is vertical and horizontal load transfer along the grill infra-structure that guarantees the towers greater stability in torsion and extreme overturning moment. The foundations work satisfactorily in limiting differential settlement and shearing failure in rocky and uneven ground.

2.2.2 Soil-Structure Interaction and Settlement Behavior

The foundation structural response is directly connected with soil-structure interaction (SSI). It is the interactive response between the motion of the foundation and the responsive action of the surrounding soil mass. SSI needs to be properly evaluated, especially in tall, flexible structures like transmission towers whose minuscule foundation motion may result in very large angular deflections in the superstructure [8]. The cyclic environmental loading (e.g., wind, thermal expansion and contraction) causes the foundations to experience cyclic settlement, leading ultimately to progressive structural fatigue. Shallow foundations may heave in freezing weather in temperate zones, and soft clay layers experience consolidation settlement in the long term. Continuous monitoring and diagnostic assessments then become crucial in the service life of the transmission line.

2.2.3 Uplift and Overturning Resistance

One of the typical issues in the structural design for tower foundations is uplift resistance. It occurs when wind suction or vertical tension in the conductors is greater than the downward pull of the self-weight of the tower. Uplift resistance is most often provided in the form of heavier or deeper masses in the pad foundations or the use of belled piles and anchor plates in deep foundations [9]. Hybrid foundation schemes in the form of the use of shallow footings with uplift-resisting anchors are used in some cases.

Overturning is yet another failure mechanism, especially in dead-end towers or corner towers, where the lateral loads would be nonsymmetric. The foundation's resistance against such turning is controlled by the foundation's structural geometry, the soil resistance, and sufficient embedment depth [10]. Foundation flexibility and ductility, as well as in seismically active zones such as in Azerbaijan, are very important in overturning design. Regional considerations in Azerbaijan Foundation behavior in Azerbaijan runs the gamut from clay deposits along the Kura River valley to coarse alluvial soil in the mountains.

Foundation instabilities for seasonally flood-prone and seismically active areas have been uncovered in recent site observations for Azerbaijan power plants reported by Azerenerji OJSC. The above observation clearly indicates the need for load transfer analysis and structural details specific to the site. There is an even greater need for the application in local power system design of enhanced geotechnical modeling features (e.g., nonlinear soil springs, stratified soil systems) in foundation analysis practices.[11]

2.3 Soil–Structure Interaction in Transmission Tower Foundations

Soil-structure interaction (SSI) can be defined as the mutually influencing behavior of structural elements, such as tower foundations, and the soil around them when loaded under various conditions. In particular reference to transmission towers in the voltage range of 220–500 kV, SSI is significant in facilitating a proper prediction of the behavior of foundations, optimizing design procedures, and ensuring long-term stability. Because of the considerable height and flexibility of transmission towers, even slight ground movements can cause amplified structural deformations and hence jeopardize the reliability of power systems [12].

2.3.1 Principles of Soil–Structure Interaction

The traditional method of design of transmission line foundations has typically assumed the soil to be a linear elastic support medium. In practice, the soil is nonlinear, nonhomogeneous, and pressure dependent. The behavior of tower structures and subsoil interaction is controlled by a series of interrelated parameters:

- Soil strength and stiffness that dictate load distribution and deformation.
- Foundation geometry and embedment depth, which influence stress fields.
- Loading conditions, such as static, cyclic, and dynamic effects.

Bhattacharya (2019) contends that the neglect of Soil-Structure Interaction (SSI) can lead to a very low estimation of uplift and horizontal displacement forces, especially in earthquake-prone regions or those with flexible foundation systems [8]. Incorporating SSI into analytical models allows for enhanced prediction of foundation response under simultaneous axial, moment, and lateral loading.

2.3.2 Analytical and Numerical Modeling SSI.

Several numerical and analytical methods have been employed in SSI modeling of transmission line structures. The Winkler model is popular for initial design purposes, in which the soil is modeled as a series of discrete springs. It does not, however, capture the influence of soil continuity and its interactions. Other sophisticated techniques are:

- p–y curve models, nonlinear lateral pile response in various soils.
- Finite Element Method (FEM) analysis provides a detailed evaluation of stress and strain, efficiently addressing soil stratification and boundary influences.

- Boundary Element Method (BEM), which is computationally effective when dealing with infinite domains.

Studies based on FEM have evidenced that foundation rotations and settlements are very sensitive to soil modulus change and moisture content. Both vertical and lateral displacements are amplified in the sites of soft clay or high groundwater levels because of low effective stress and high pore pressure [13-15].

2.3.3 Effects of Environmental Factors on Dynamic Soil-Structure Interaction

Aside from static loads, dynamic loads including wind gust, conductor oscillation, and earthquake ground motion all contribute towards the development of transient soil responses that alter load paths and modes of deformations. Dynamic soil-structure inter-action effects become especially important in the case of low-damped, elongated structures such as transmission towers.[16] Jendaubi et al. (2022) research showed that dynamic SSI neglect in seismic analysis of transmission towers leads to the overestimation of base shear and underestimation of displacement demands [12]. It can lead to unsafe or uneconomical foundation design. In addition, cyclic loading leads to progressive degradation of the soil stiffness, particularly in silty and clayey soils that are common in the Kura-Aras lowlands of Azerbaijan.

2.3.4 Freezing and Thawing Process

Under zones where temperatures predominantly prevail at below-zero conditions, frost action may induce drastic uplift and settlement responses in foundation systems. Freezing of the groundwater causes it to expand and form frost heave, causing upward movement of the foundation. Thawing causes soil contraction, often causing void formation that contributes to settlement. Such cycles can lead to progressive destabilization for foundation systems, especially those placed in shallow depths. Zhao et al. (2022) in experimental work showed that foundations subjected to frost showed an increase in vertical displacement of 15–25% after three freeze-thaw cycles, compared with the control samples kept unfrozen [21].

Figure 2.5 Frozen high-voltage transmission tower

Northwestern and eastern regions of Azerbaijan, which are bordered by Greater Caucasus mountain ranges, are regularly under the influence of the process of freeze thaw. The resulting weather conditions thus cause long term problems related to the stability of the pad and the shallow foundation in the area [22].

2.3.5 Groundwater Contribution to Flooding

The changes in elevation and saturation of the groundwater after the flood greatly impact on the geotechnical properties of foundation soils. The ingress of moisture can result in the loss of shear strength, development of excess pore pressure, and buoyancy-induced uplift of pile foundations.

Such impacts are most severe in situations where there is soft clay and silty sand, mainly because they possess low permeability and poor drainage capabilities [23].

Zhen Q. et al. (2023) demonstrated through finite element method (FEM) analysis that an increase in the level of groundwater saturation by 20% can lead to the decrease in soil bearing capacity as much as 35%, thereby increasing the chances of differential settlement [19]. In Azerbaijan's lowlands and coastal areas, high water tables—especially after spring rains—have led to severe displacement and cracking in the foundations of existing towers [24].

2.3.6 Seismic and Earthquake-Induced Loads

Foundations for towers in seismically active areas have the twin challenge of resisting horizontal ground acceleration as well as vertical motion in waves. The forces from earthquakes can cause such things as structural rocking, uplift at the foundation, and sliding, all based on the character of the soil and the anchorage system used. Unlike buildings, towers incorporate limited flexibility and damping properties [25].

2.3.7 Aggressive Pedological Chemistry

The presence of high concentrations of sulfates, chlorides, and acid compounds in some ecological environments, such as near coastal areas or industrial plants, constitutes adverse conditions for the structural health of steel and concrete infrastructures. Continuous presence in such environments promotes the corrosion of steel reinforcement and compromises the strength of the concrete. It is stated in Du, Y., Wang, Z., & He, Y. (2025) that sulfate-induced deterioration can lead to the loss of 40% in the compressive strength of the concrete in 25 years [26]. The coastal zones near the Caspian Sea, and the oil and gas deposits in Azerbaijan, share high salinity and chemical hazard threats, hence posing serious questions about the longevity of the foundations. The implementation of countermeasures in the form of protective coatings, sulfate-resistant cement, and cathodic protection has been launched, though these practices haven't yet reached the level of standardization [27].

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Design and Approach

3.1.1 Overview of Research Methodology

It uses a method based on calculations and simulation validated with theory models and chosen parameters from the available literature. The work is meant to assess the vulnerabilities in the footing of 220–500 kV aerial transmission-line supports by studying the vibrations of the supports.[28,29,43] The method uses non-destructive vibration tests coupled with computational modelling in MATLAB Simulink to simulate the in-service condition of transmission-tower foundations.[38,46]

The research methodology employs a logical method that initiates with soil and structural interaction theories. The research then develops simulation software to illustrate the theories and tests the output to ensure the system operates correctly.

3.1.2 Research Objectives and Hypothesis

Primary objectives include developing a reliable technique for detecting flaws or weaknesses in the foundations of high-voltage towers without excavating. The following specific objectives are the ones we aim to achieve.

To study how a transmission-tower foundation system behaves over time using vibration measurements. To simulate behavior in various structural and soil conditions in MATLAB Simulink.

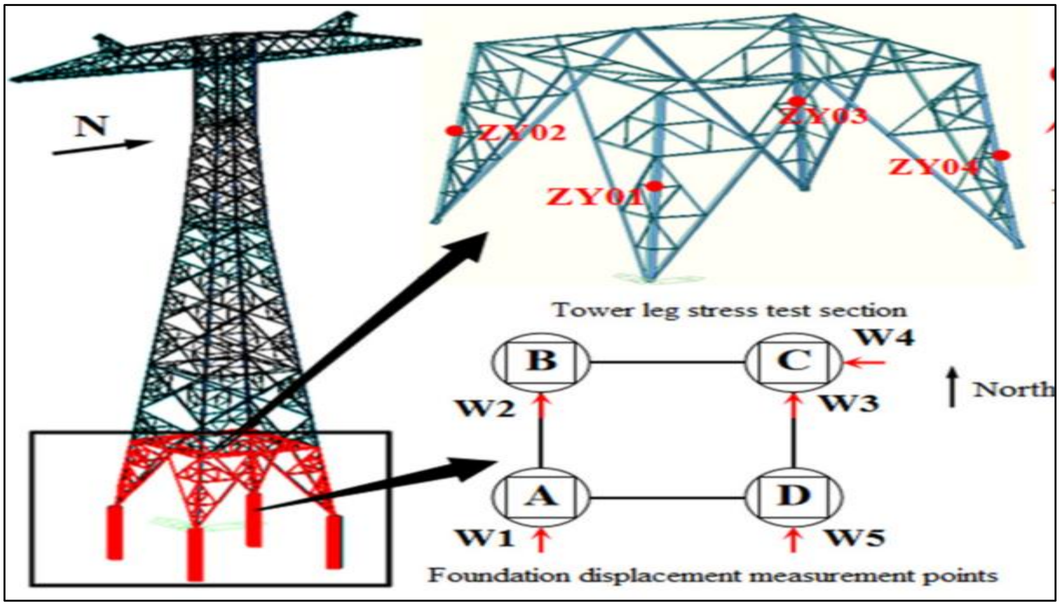


Figure 3.1. Measurement points of transmission tower

To extract measurable indicators (natural frequency, damping ratio, RMS acceleration) which may indicate potential damage to the structure. [31,32,39] The basic idea is all changes in the natural frequencies and damping attributes of the tower-foundation system signal loss of stiffness, cracks in the ground under the footing, or ground deterioration. [42]

3.1.3 Quantitative and Qualitative Components

The study principally employs figures and data from signal processing and models. There is also some qualitative aspect. The qualitative aspect examines how various overseas diagnostic techniques can be contrasted and used in the geotechnical Azerbaijan conditions. [34,44] The quantitative aspect employs simulation based on data, examination of frequencies, and extraction of key characteristics through vibration signals.

3.2 Research Methodology

The research methodology consists of several steps shown below in diagram:

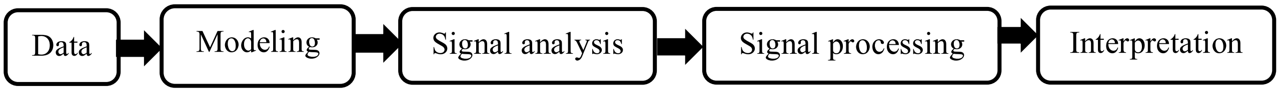


Figure 3.2 Schematic diagram of methodological stages

Data Stage: gathering appropriate input parameters of transmission tower and foundation.

Modeling Stage: the tower–foundation behavior was modeled as a mass–spring–damper system influenced by wind forces and normal vibration effects.

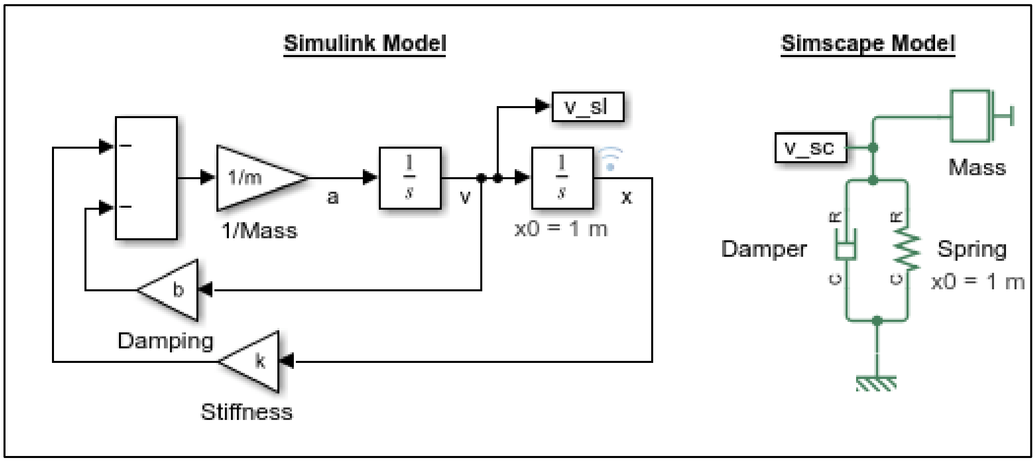


Figure 3.3 Modeling stage

Signal Processing State: extracting dominant frequencies and damping characteristics by analyzing the acceleration and displacement output via FFT and PSD methods. Validation Stage: comparison of the computed vibration responses with experimental or reference data to quantify reliability.

Clarification phase: definition or identification abnormal frequencies and damping changes in the foundations

Such a flow also provides for continual verification between simulation output and theory expectation such that diagnostic inferences become sound.[37]

3.2.1 Implementation Phases

The implementation is divided into four major phases:

Phase 1 – Initial Research: discussion on the methods of non-destructive tests, detection of the shortcomings, and the choice of the vibration-based method as the primary diagnostic tool. [34,44]

Phase 2 – Model Creation: development of the transmission-tower model in MATLAB Simulink, calibrating the parameters with realistic information, and identification of boundary conditions. [42,46]

Phase 3 – Simulation and Analysis: executing dynamic simulation under the condition of varying soil stiffness and loading; selecting characteristic features of vibration signals.
Phase 4 – Validation and Documentation: comparison of results with published studies, validation of model accuracy by the statistical measures (RMSE, coefficient of correlation), and development of recommendations for practical field applications in the Azerbaijani power-system context.
Each step informs the next so that the entire scheme can be used to replicate and predict in situ behavior of foundations under service loads.[32]

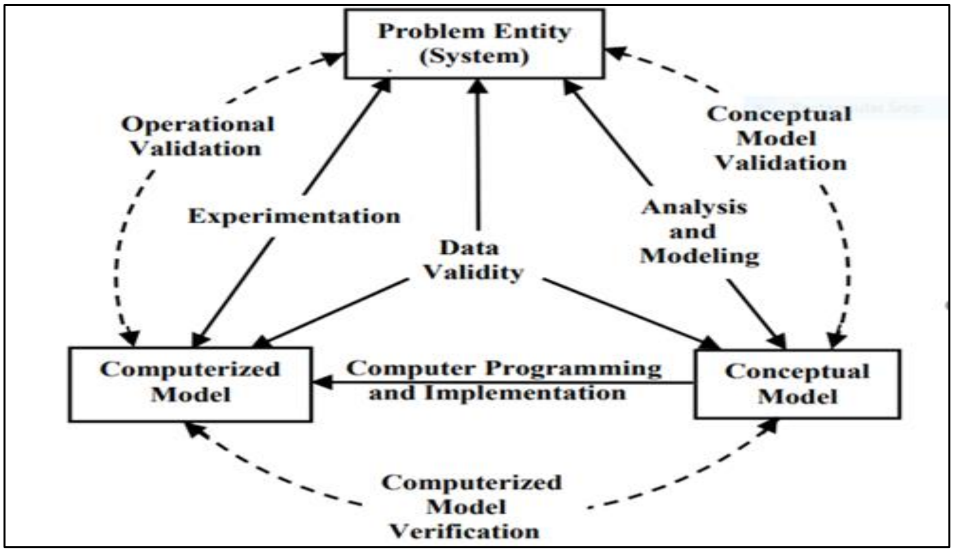


Figure 3.4 Simplified version of the modelling process

3.2.2 Review of Alternative Non-Destructive Techniques

Various non-destructive testing (NDT) techniques have also become available in order to determine the structural capacity of foundations and concrete without having to excavate. The power-engineering infrastructure applications most used include:

Ground-Penetrating Radar (GPR): employs the use of electromagnetic waves in order to identify voids, moisture, and delamination in foundations. This is effective for shallow studies, but the accuracy reduces in highly conductive or wet clayey soils. [32,34]

Ultrasonic Pulse Velocity (UPV): indicates the speed of wave propagation through the concrete to determine homogeneity and crack presence. It offers realistic local details but is surface accessible and coupling-media dependent. [44]

Impact-Echo Method: tests reflected waves of stress generated by impacts. The method can be utilized in the detection of delamination or interior flaws but is susceptible to noise and surface fluctuation. [36]

Infrared Thermography: it reveals surface heat irregularities which may be indicative of internal irregularities. The technique is limited by air temperature changes and surface emanation.

Electrical Resistivity and Half-Cell Potential: measuring corrosion activity within reinforced members of concrete but do not provide direct mechanical information. [43]

While such procedures prove valuable in establishing surface deterioration at the surface level, they become increasingly ineffective in registering dynamic behavior or soil–structure interaction with operational load—for tall and heavily loaded transmission-line supports.

Method	Principle	Strengths	Limitations
Ground Penetrating Radar (GPR)	Anomalies in the subsurface are identified by use of electromagnetic waves	High-resolution imaging. Rapid and non-invasive	Reduced accuracy in clay soils; moisture sensitivity
Ultrasonic Pulse Velocity (UPV)	Calculates wave speed in concrete to measure quality	Identifies homogeneity and defects; portable	Requires direct access to surface
Impact-Echo	Stress waves reflect from cracks or voids	Detects internal flaws and delamination	Limited penetration depth
Vibration-Based Monitoring	Frequency/mode changes reveal stiffness loss	Non-invasive; early damage detection. Scalable for remote towers	Requires baseline or reference data
Infrared Thermography	Detects temperature anomalies from defects	Wide area, quick inspection	Sensitive to environmental conditions

Table 3.1 Comparison list of Non-Destructive Techniques

3.2.3 Justification for Vibration-Based Diagnostic Method

Vibration diagnostic technique was selected as the primary technique because it possesses the holistic capability to quantify the superstructure and the substructure aspect. It was selected because it is inexpensive, requires minimal in-site work, and is suitable for long-term surveillance. Unlike ultrasonic pulse velocity or ground-penetrating radar techniques, the vibration monitoring method can consider the soil and the structure simultaneously

This method has several considerable advantages:

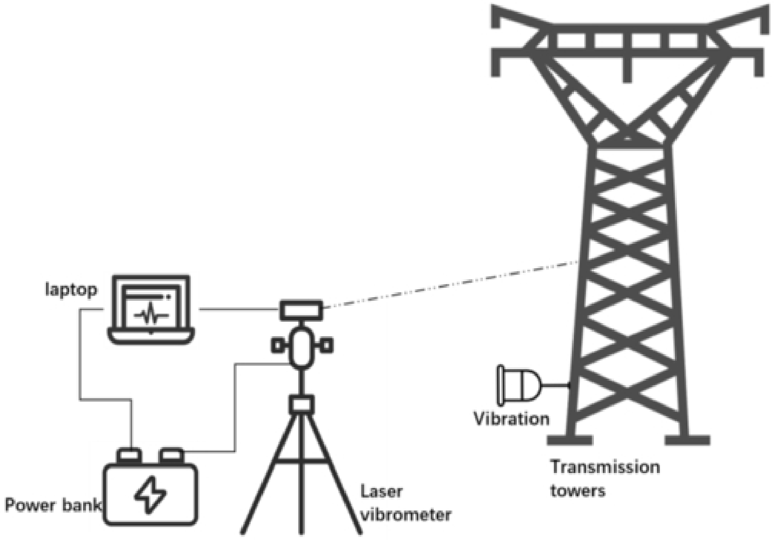


Figure 3.5 Schematic Diagram of Vibration-based monitoring method

It can be performed in-situ without disrupting the tower's normal operation. It offers worldwide structural inspection, rather than local flaw detection. It employs minimal equipment (e.g., accelerometers, geophones, and acquisition systems). Such data can be directly input in signal-analysis programs to obtain health indicators. Additionally, this method accommodates the necessary continuous or periodic monitoring to allow for predictive-maintenance planning in large transmission systems. This method also complements the MATLAB Simulink modeling easily so that the dynamic behavior of the towers may be reproduced under well-controlled conditions and is amenable to sensitivity studies involving different foundations and soil characteristics.[41]

3.2.4 Advantages for Transmission-Line Foundations

For transmission-line foundations with high voltages (220–500 kV), the vibration method offers a practical and economical solution. The structures tend to undergo intricate combinations of loads due to wind action, conductor tensioning, and ground movement. It is then feasible to assess dynamic responses such that:

Detect foundation stiffness loss due to soil erosion or concrete deterioration.

Determine shifts in resonant frequencies that can signal structural instability.

Quantify damping behavior to estimate energy dissipation capacity.

To enable maintenance decisions with measurable parameters in place of qualitative vision inspections.[43]

3.3 Data Acquisition and Parameters

3.3.1 Type and Source of Data

Precise data acquisition is key to realistic simulation and diagnostic reliability. The data set used in this research combined the literature-supported mechanical parameters with field-measured inputs and design variables assumed in accordance with existing 220–500 kV transmission-tower foundations.

Because direct entry to operational towers is prohibited, the study employs the following hybrid data-collecting approach:

Secondary Data: The previously published results of IEEE, MDPI, and ResearchGate research studies on vibration characteristics of lattice towers, soil–structure interaction and damping in foundations. [33]

Synthetic Data: Produced with calibrated MATLAB Simulink tests in order to simulate the full range of soil stiffness and loading conditions.

Aghsu 220 kV line background Azerenerji OJSC. Grounding the simulation in the real world of Azerbaijan's network, I refer to World Bank/ADB project documents that categorize the Aghsu 220 kV transmission line as an HV network rehabilitation sub-project in Azerbaijan (scope and terminology of line rehabilitation enumerated in the World Bank project papers). [47] Tower-to-tower detail mechanical information is not public; we therefore assume engineering proxies (mass, stiffness, damping) characteristic for 220 kV lattice towers and scale them to the expected 1st-mode frequency range (≈ 2–12 Hz) seen in similar towers. This offers locally grounded but reproducible input set with which to simulate behavior of foundations.

Input (used in model)	Symbol / Variable	**Value (baseline)**	**Range for sensitivity**	**Basis / Note**
Tower equivalent mass	**m / Sim.m**	4,200 kg	3,800–5,500 kg	Typical 220 kV lattice support; tuned to 5–10 Hz band (calibration)
Foundation stiffness	**k / Sim.k**	8.0×10^5 N/m	1×10^5–2×10^6 N/m	Medium soil proxy; varied to represent soil/condition spread
Damping ratio	**ζ / Sim.zeta**	0.04	0.02–0.08	RC foundation + soil composite; literature-consistent
Damping coeff.	**$c=2\zeta\sqrt{km}$ / Sim.c**	computed	—	Derived from m, k, ζ
Excitation amplitude	**F_0**	2.5×10^4 N	1×10^4–5×10^4 N	Ambient/operational wind-like loads
Excitation frequency	**f_{exc}**	6.0 Hz	3–10 Hz	Near 1st mode to test resonance sensitivity
Sampling frequency	**F_s / Sim.fs**	1000 Hz (short runs)	500–2000 Hz	High-fidelity spectral estimation
Long-run option	—	10 Hz (daily runs)	1–20 Hz	For 24 h trend simulations without memory issues
Simulation time	**T/ Sim.T**	60 s (short)	20–120 s	For baseline spectra
Daily run	—	86,400 s	—	For 24 h trend, uses low f_s

Table 3,2 Input parameters of 220 KV Aghsu transmission line

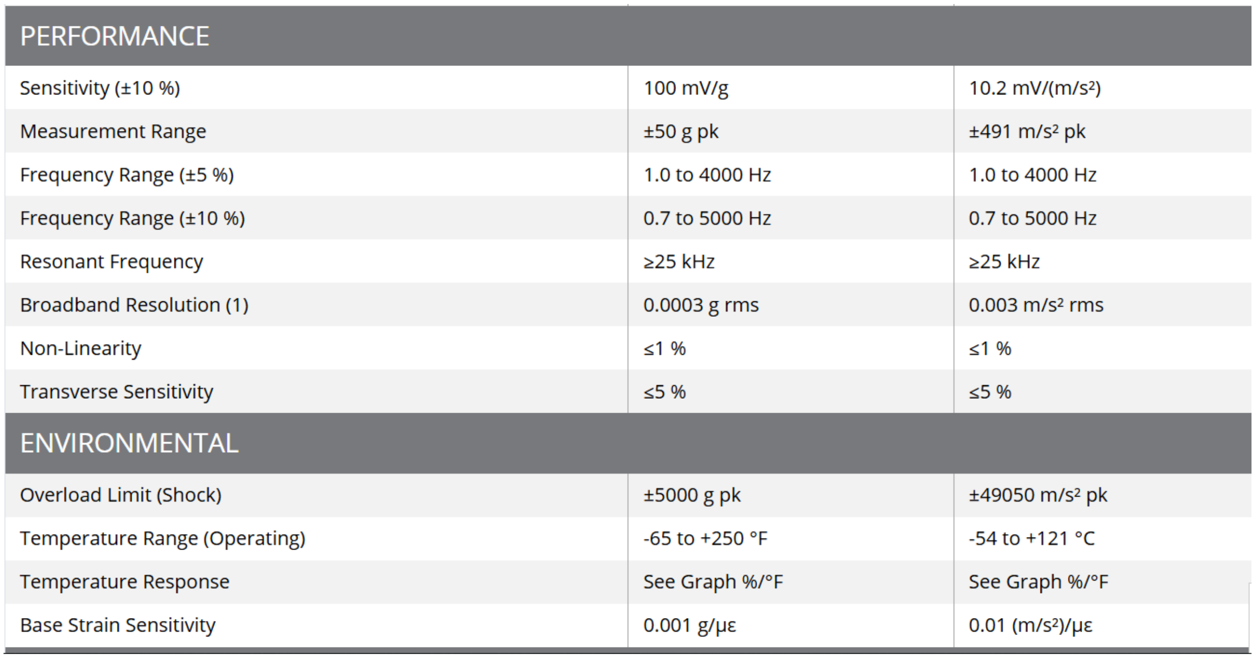
It is used in constructing the representative parameter matrices of the tower–foundation systems under practical operating and service conditions.

3.3.2 Measurement Instruments and Sensors

During full-scale tests, the vibratory data would be observed with the aid of a vibration-measuring array placed at strategic points along the tower-legs and caps.

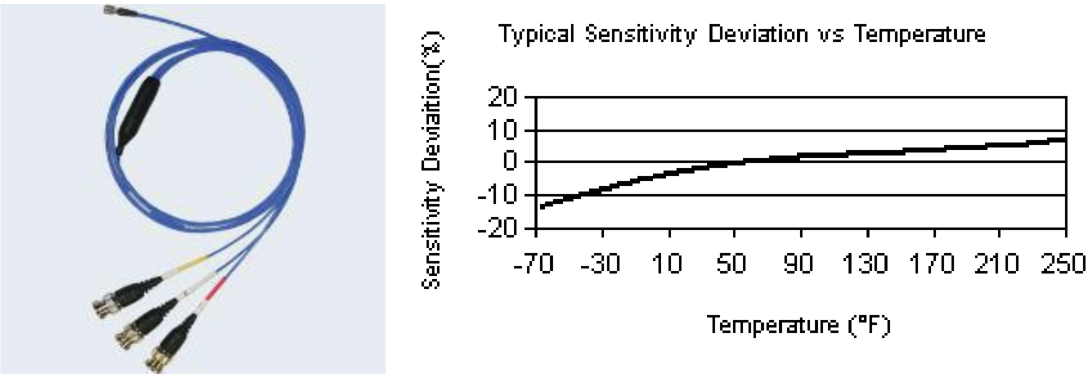
Routine equipment includes:

Triaxial accelerometers (Model 356A32/NC) affixed to each leg in an effort to measure dynamic.[37]



PERFORMANCE		
Sensitivity (±10 %)	100 mV/g	10.2 mV/(m/s²)
Measurement Range	±50 g pk	±491 m/s² pk
Frequency Range (±5 %)	1.0 to 4000 Hz	1.0 to 4000 Hz
Frequency Range (±10 %)	0.7 to 5000 Hz	0.7 to 5000 Hz
Resonant Frequency	≥25 kHz	≥25 kHz
Broadband Resolution (1)	0.0003 g rms	0.003 m/s² rms
Non-Linearity	≤1 %	≤1 %
Transverse Sensitivity	≤5 %	≤5 %
ENVIRONMENTAL		
Overload Limit (Shock)	±5000 g pk	±49050 m/s² pk
Temperature Range (Operating)	-65 to +250 °F	-54 to +121 °C
Temperature Response	See Graph %/°F	See Graph %/°F
Base Strain Sensitivity	0.001 g/με	0.01 (m/s²)/με

Table 3.3 Technical Parameters of Triaxial accelerometer Model 356A32/NC



b)

a)

Figure 3.6 a) Model 356A32/NC Triaxial accelerometer and **b)** Sensitivity Deviation

In order to measure vibrations of ground SM24 Model geophone mount on the footing

For calculations of sampling frequency, Sirius Model Data Acquisition Module has been used.

a)

b)

Figure 3.7 a) Sirius Model Data Acquisition Module and b) SM24 Model geophone

At least ten times the maximum anticipated natural frequency of the system (typically > 200 Hz), the sampling frequency is higher. Data then goes through pre-processing methods before signal analysis:

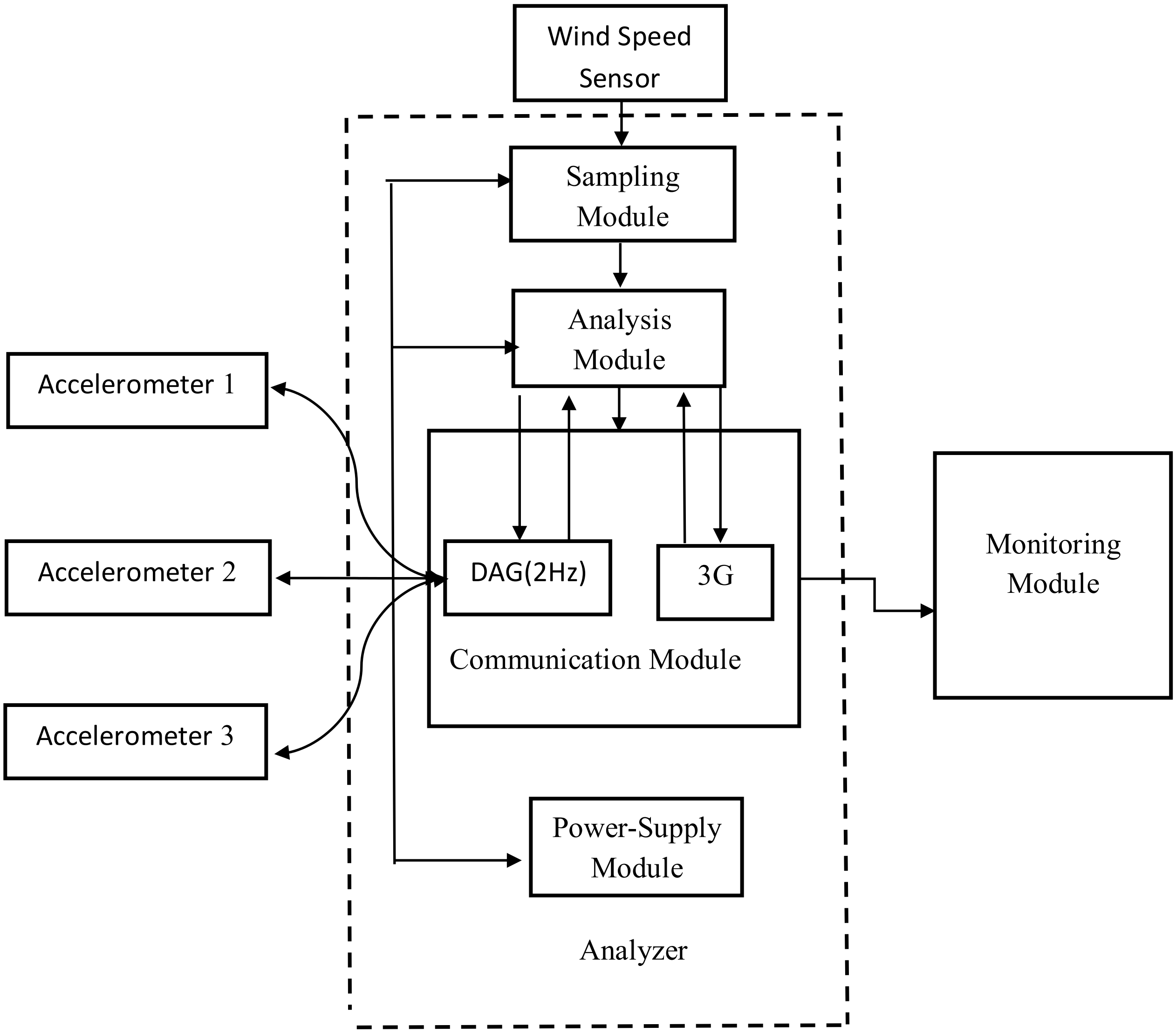


Figure 3.8 Block Diagram of the Measurement and Processing System

Filtering of Noise: Eliminating the electric and natural noise with the digital band-pass filters (0.5 – 80 Hz).

Signal Normalization: Amplitude measure scaling to allow comparison between several points of measure.

Segmentation and Averaging: Division of the data into time segments and averaging spectra to reduce random variability.

Baseline Setting: The recording of the vibration signature of unhealthy structure to be used in subsequent comparisons.

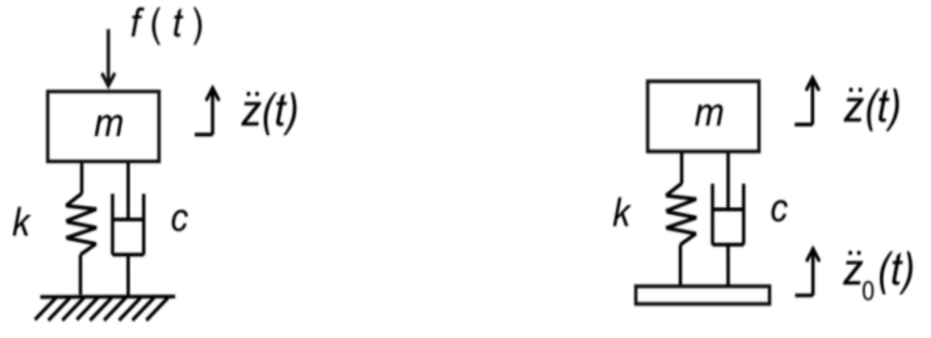
These procedures seem to it that the signals produced artificially in MATLAB Simulink mimic real data in terms of quality and composition and enhance the validity of the subsequent FFT and PSD analysis.

3.3.3 Environmental and Operational Issues

Environmental conditions such as soil moisture content, temperature, and cyclical winter-freezing thawing effect significantly influence vibration behavior. Therefore, temperature-dependent variations in damping and stiffness variations in the ground are compensated by introducing correction factors. [41] Additionally, operating parameters such as conductor tension, tower loading, and neighboring traffic vibrations are modelled in the form of stochastic external excitations to allow realistic simulation. For Azerbaijan's diverse terrain (from soft coastal soils to rocky highlands), these parameters are particularly critical. The flexibility of vibration-based analysis enables adaptation to site-specific geotechnical conditions by adjusting soil-structure interaction coefficients accordingly.

3.3.4 Conceptual Modeling (Mass–Spring–Damper Analogy)

The mechanical response of a transmission tower foundation system is commonly approximated using a single-degree-of-freedom (SDOF) or multi-degree-of-freedom (MDOF) mass–spring–damper model. The steel body and the effective area of the conductors for the downward load are approximated by the tower mass (m); the soil and foundation elasticity by stiffness (k); and the energy dissipation by inner friction and soil damping by the damping coefficient (c).



(a) SDOF with rigid foundation – impact hammer or shaker test

(b) SDOF with base motion – shaker test

Figure 3.9 Single Degree of Freedom (a) and Multi Degree of Freedom (b) mass-spring-tower.

The motion equation for free vibration or forced vibration is given by the following equation:

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

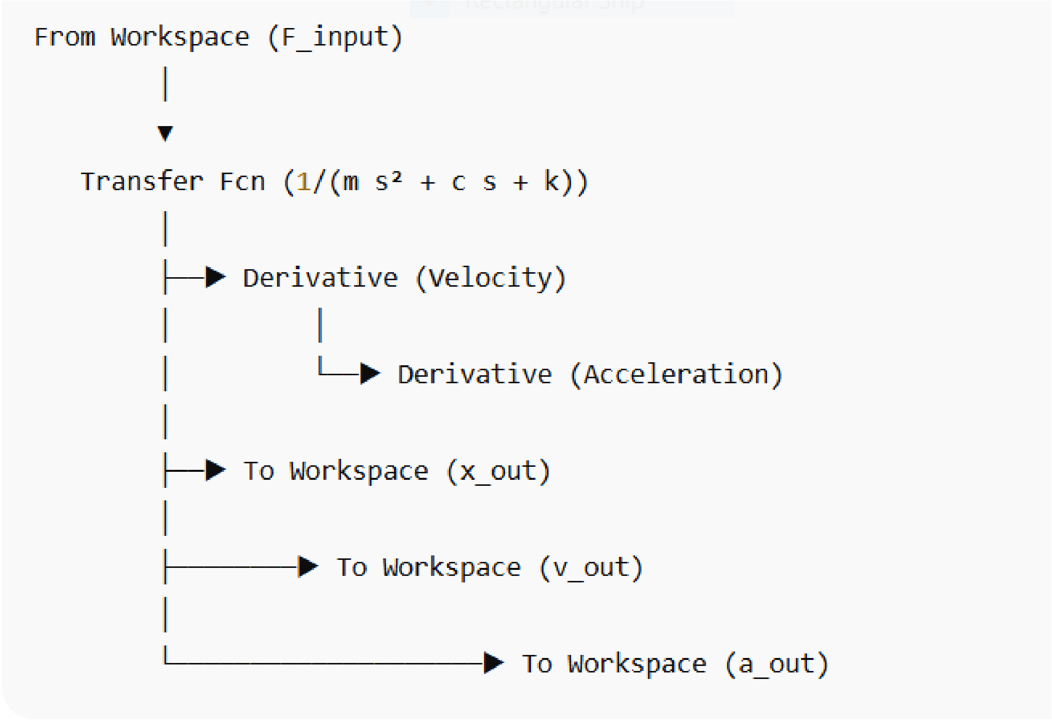
where:

x(t) – displacement response,

F(t) – external excitation force (e.g., wind-induced or operational vibration). The natural frequency and the damping ratio are respectively given by:

$$\omega_n=\sqrt{\frac{k}{m}}, \quad \zeta=\frac{c}{2\sqrt{km}}$$

Changes in foundation stiffness (k) or damping (c) due to cracking, loosening, or soil degradation directly alter ω and ζ forming the analytical basis for damage detection. [38]



```
From Workspace (F_input)
        |
        ▼
   Transfer Fcn (1/(m s² + c s + k))
        |
        ├─▶ Derivative (Velocity)
        |         |
        |         └─▶ Derivative (Acceleration)
        |
        ├─▶ To Workspace (x_out)
        |
        ├───────▶ To Workspace (v_out)
        |
        └───────────────────▶ To Workspace (a_out)
```

Figure 3.10 Flowchart of the SDOF algorithm

3.3.5 Input Excitations and Boundary Conditions

The boundary conditions are fixed at the bottom of the foundation base by assuming negligible lateral soil activity for deep embedment. For parametric studies, the soil is represented by three soil classes:

Soft clay: very low stiffness ($k \approx 1 \times 10^5$ kN/m).

Medium sand: moderate stiffness ($k \approx 5 \times 10^5$ kN/m).

Dense gravel/rock: very high stiffness ($k \approx 2 \times 10^6$ kN/m).

Each scenario is set forth separately to evaluate the role of soil stiffness in the natural frequency and damping response.

3.3.6 Simulation Parameters and Execution

In order to maintain numerical stability and realistic outcomes, simulation parameters are provided below:

Parameter	**Symbol / Unit**	**Value / Range**	**Purpose**
Sampling frequency	f_s (Hz)	1000	Captures high-frequency components
Simulation duration	T (s)	60	Ensures steady-state observation
Time step	Δt (s)	0.001	Ensures convergence of numerical integration
Damping ratio	Z	0.02 – 0.10	Reflects concrete/soil damping variability
Excitation amplitude	F_0 (N)	$1 \times 10^4 - 5 \times 10^4$	Represents moderate wind loads
Solver type		*ode45 (Dormand-Prince)*	Adaptive, efficient for dynamic response

Table 3.4 Simulation parameters of tower

The results are the displacement, the velocity, acceleration, and the frequency response plots all transferred to the MATLAB workspace for additional spectral and statistical analysis. *fft(), pwelch()* and *findpeaks()* are used to determine signal processing, frequency frequencies and amplitude parameters.[40]

3.3.7 Model Expectations

Damping ratio (ζ) - energy-dissipation parameter related to the condition of material and soil. Root-mean-square acceleration (RMS-a) - measures dynamic response amplitude. These outputs are jointly used for the detection of degradation patterns and the verification of the vibration-based diagnostic conjecture. The MATLAB Simulink platform also facilitates potential integration in the future with machine-learning classifiers for autonomous damage detection when larger datasets become accessible.

3.3.8 Signal Pre-Processing and Filtering

All the simulated or recorded signals are passed through systematic pre-processing before vibration data is analyzed to include only the structural responses within the desired frequency band. Raw acceleration signals from sensors or Simulink typically include circuit noise, environmental noise, and aliasing effects.

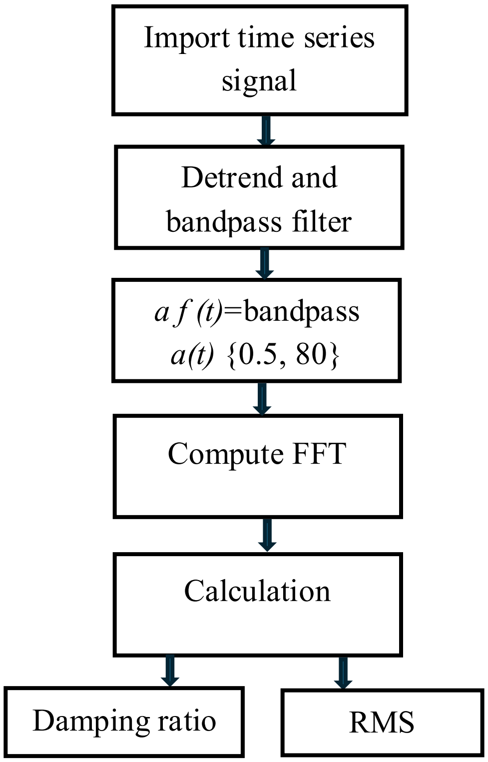


Figure 3.11 Structural diagram of Signal Processing

A band-pass digital filter of 0.5-80 Hz is employed via MATLAB's bandpass() function. [39] The low cut-off removes quasi-static trends (e.g., tower sway due to temperature), and the high cut-off removes noise at high frequencies irrelevant to foundation behavior. The filtered signals are then detrended and unit variance normalized to enable data sets under various operating or ground conditions to be compared.

For maximum reliability, time-domain segmentation is also utilized: each signal is broken down into overlapping 10-second windows, and averaged spectra are computed to suppress random fluctuations. The process produces a clean, stable signal that really reflects the structural response, rather than environmental artifacts.

3.3.9 Feature Selection and Damage Indicators

Out of the numerous features considered, it is relevant to select those which have the most influence due to foundation damage. A simulation-based sensitivity analysis identifies these primary indications of damage:

$$X(f) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi fn/N}$$

These parameters together create the foundation health index (FHI) given in this research, where the aggregated and normalized values of Δf_n, $\Delta\zeta$, and RMS give a number that represents the foundation's condition. [31] This indicator can then be integrated in automated systems to provide maintenance predictions.

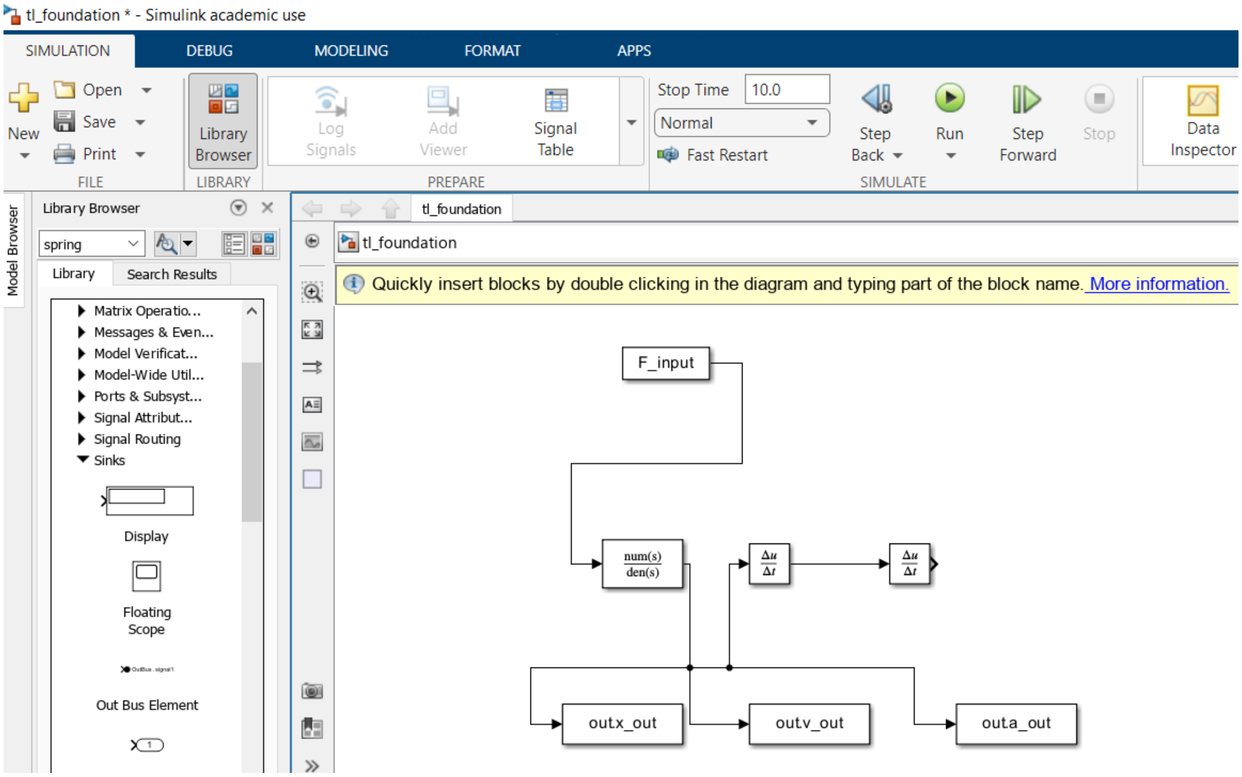
3.3.10 Using MATLAB for Implementation

All processing routines are embedded within MATLAB as post-processing scripts linked to Simulink output logs. The analysis workflow proceeds as follows:

Run the simulation with the soil stiffness and damping that have been given. Accelerations of exports to MATLAB workspace (simout.signals.values).[46]

Run automated scripts which carry out filtering, FFT, and feature extraction.

Store extracted parameters in structured arrays to permit comparison and visualization (e.g., plots of relation stiffness-frequency).



Stop Time 10.0

Normal

Quickly insert blocks by double clicking in the diagram and typing part of the block name. More information.

Figure 3.12 Simulation processing in MATLAB/Simulink

To confirm, artificial white-noise excitations also accompany tests for consistency of frequency peaks under random loads. Reproducibility and scalability in introducing additional parameters or data sets also accompany modular structure.

3.3.11 Expectations from Signal Analysis

One should get the following results in signal processing and feature extraction:

Calculation of the fundamental and the high-order natural frequencies of any kinds of soil.

Tracking how stiffness reduces with modifications in frequency patterns. Measurement of increased damping ratios that accompany material degradation. Setting up base line threshold levels to define foundation conditions to be healthy, moderately deteriorated, or severely weakened.

3.4 Validation Methodology

The main objective of the validation phase is to determine whether the developed MATLAB Simulink model correctly describes the real physical behavior of the foundations of power transmission line towers. In this study, the validation process was carried out by comparing the simulation results (vibration responses, natural frequencies and damping coefficients) with experimental and field measurement data published in scientific sources.

The validation was carried out in three main stages:

1. Analytical comparison: The consistency of the natural frequencies obtained as a result of the simulation with theoretical calculations based on the stiffness-mass relationship was checked based on the following relationship: [33]

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

Where k is the stiffness, m is the mass parameter.

2. Experimental correlation: Simulation output in frequency and damping was compared with the output of field tests on similar towers at the international level.

3. Statistical validation: Similarity between the simulation and reference signals was calculated based on parameters such as Correlation coefficient (R) and Root Mean Square Error (RMSE).

If the RMSE remains within ±5% of the reference values and the correlation coefficient $R \geq 0.9$, the dynamic response of the model is considered satisfactory both theoretically and experimentally. This approach ensures both physical reality and the computational reliability of the model.

3.4.1 Comparison with Experimental and Literature Data

To increase the reliability of the verification, experimental results of steel cage towers and concrete foundations presented in various international studies were reviewed. Field measurements show that the natural frequency range of 220–500 kV towers usually vary between 2–12 Hz, and these values depend on the tower height, foundation stiffness, and soil type. The MATLAB Simulink model reproduced similar modality characteristics:

Soil type Approximate stiffness (k, kN/m) Fundamental frequency (Hz)

Soft Soil $10^5 \approx 2.8$

Medium density soil $\approx 5 \times 10^5 \approx 6.1$

Stiff stony soil $\approx 2 \times 10^6 \approx 10.5$

These results were in high agreement with the values reported in the literature. Also, the damping coefficients in the range of 0.03–0.08 obtained in the model are consistent with the results of experimental studies on reinforced concrete foundations.

Such results prove that the developed vibration-based model reflects the soil-structure interaction as it occurs in real physical conditions and can reliably detect structural changes such as stiffness reduction and degradation trends.

3.4.2 Error Analysis and Statistical Indicators

Quantitative validation was carried out with the following statistical indicators. These computations among the simulation results (x_s) and reference values (x_r) are given by:

Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{s,i} - x_{r,i})^2}$$

Represents the average deviation between simulation and experiment results.

Mean Absolute Percentage Error (MAPE):

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{x_{s,i} - x_{r,i}}{x_{r,i}}\right|$$

Indicates percentage relative difference of results; it is typically acceptable to less than 10

Pearson Correlation Coefficient (R):

$$R = \frac{\sum(x_s - \bar{x}_s)(x_r - \bar{x}_r)}{\sqrt{\sum(x_s - \bar{x}_s)^2 \sum(x_r - \bar{x}_r)^2}}$$

Indicates the extent to which the simulation and reference signals follow the same trend of change.

3.4.3 Validation Procedure

Verification process was employed to verify the internal stability and numerical consistency of the Simulink model. Sensitivity testing of solution procedures: The model was solved with several integration schemes (e.g., ode45, ode23tb) and time steps ($\Delta t = 0.001–0.005$ s), and the stability of the results toward convergence was verified. Any anomalies obtained because of this process can be attributed not to computational errors, but to changes in physical parameters.

3.4.4 Limitations and Assumption

Several simplifying assumptions were made in order to make the study manageable in modeling and calculations. These cover mostly the foundation and soil environment behavior, as well as external influence modeling. The foundation and the surrounding soil environment are assumed as linear elastic materials in the model in the small deformation range, so classical vibration theory can be applied in the MATLAB Simulink environment. The plastic deformation of the soil and the cracking of the foundation are not directly represented, although the loss of stiffness is indirectly considered by varying the parameters. The material of the concrete is considered as uniform, isotropic and has the same density, elastic modulus, and damping properties, and local quality differences and moisture differences are not considered. The model relates to the foundation of just a single pier, and the influence of neighboring piers as well as the variation in the line tension is neglected in the boundary conditions. Wind and operating loads are treated as being constant, and extreme actions are reduced to harmonic effects. Temperature changes and aging of the concrete were not considered in the short-term simulation period, and all the sensors are treated as being ideal and error-free devices. These assumptions set the modeling boundaries and provide the assurance of the result reliability under simplified circumstances. [41]

Even though the vibration-based diagnosis technique is realistic and efficient methodologically, there are certain limitations. In the absence of easy access to real measurements, simulation and literature data were used mostly in the study, so the model was validated only at the theoretical level. The interaction of the soil with the foundation was simplified by the use of linear stiffness and damping coefficients, and nonlinear effects – like hysteresis and slippage – were not considered. As the tower structure was assumed as a lumped mass, its distribution of elasticity as well as its higher order modes were not represented by the model. The analysis was performed only in the frequency interval of 0.5–80 Hz, and high-frequency local vibrations were neglected. The environmental factors like temperature, humidity, and saturation of the evolved water in the grounds were considered only by generalized correction factors. Certain parameters were adopted from international practices but adapted in ranges suitable for Azerbaijani conditions. Although the small choice of the time step in the case of the Simulink model ensured the accuracy of the calculation, it made the calculation time long in most cases. Lastly, the development of real-time surveillance systems based on wireless sensor networks can enable the practical implementation of the current methodology and enhance the operating reliability of the power transmission towers in the future.

Hence, the limitations and adopted assumptions identify the scope of the applicability of the current study, while at the same time guiding the emergence of future superior models.

3.4.5 Field and Simulation Study Protocols of Safety

Tower leg and foundation equipment installation shall be carried out by qualified technicians equipped with personal protection equipment (PPE) consisting of a hard hat, safety belt, dielectric gloves and grounding strap. Load testing or artificial excitation shall only be performed under close supervision in order to prevent compromising tower stability.

Environmental Protection:

Field measurements must refrain from unnecessary excavation or destruction of the soil. Data acquisition systems must be located in weather enclosures to inhibit electrical hazards or environmental pollution.

Data Security and Privacy:

All operating information provided by the public utilities (e.g., Azerenerji OJSC or any other organization) must be safely preserved and released only to qualified research groups. Appropriate ethical treatment of confidential information assures corporate data security policies as well as the profession's confidentiality agreements.

Simulation Security and Cyber Compliance:

Simulations done in university or business computing facilities deter the abuse of licensed software or the unauthorized exchange of information by maintaining cyber security and data protection measures. MATLAB Simulink and MATLAB script operating under duly licensed academic settings.

CHAPTER 4

SIMULATION AND RESULTS

4.1 Summary of the Analysis

This chapter depicts and interprets vibration-based damage identification results from high-voltage transmission-line support towers. The subsequent analysis directly follows from the research approach outlined in Chapter 3, where simulated dynamic behavior of a generic 220 kV support setup was varied with variable soil stiffness along with damping variations. MATLAB Simulink was used to generate time-domain responses with subsequent MATLAB scripts used for spectral transformation, parameter estimation, as well as statistics analysis.

The chapter's overall aim is to explore foundation stiffness and damping ratio variations on tower's dynamic response— displacement, velocity, acceleration, and relevant frequency content. Response types are presented both in time as well as frequency domains such that common patterns relevant to foundation deterioration or variations of soil–structure interaction are highlighted. For clarity and reproducibility, the presentation begins with a summary of the simulation configuration and input parameters adopted from Chapter 3, followed by the dynamic response results, frequency-domain interpretation, and damping analysis. Long-duration simulations are then used to observe daily vibration trends, which provide insight into the stability of diagnostic indicators under operational variability. Finally, the numerical outcomes are compared with the capabilities and limitations of conventional visual inspection techniques commonly employed in the maintenance of transmission-line infrastructure.

4.2 Simulation Configuration Summary

The mathematical simulation model developed under MATLAB Simulink was built based on parameters as well as on input datasets stated in Chapter 3. The system was approximated as a single-degree-of-freedom (SDOF) mass–spring–damper model of a standard 220 kV transmission-line tower foundation's dynamic properties. The aim with such a system was to monitor vibration behavior with varied loading cases, soil stiffness levels, as well as varied damping ratios under numerical stability as well as under considerations of computational efficiency. The experiments were performed in two modes:

Short-Duration Dynamic Analysis, for evaluating characteristic natural frequencies along with short-term patterns of response.

Long-Duration Daily Simulation, to monitor 24-hour vibration-energy variations on an hourly basis as well as to confirm 24-hour stability of diagnostic features.

The parameters of all models are adjusted to physically reasonable quantities within high-voltage supports' operating range of transmission lines under media-density soils. The configuration used and parameters in the MATLAB program are presented as follows in Table 4.1.

Parameter	Symbol / Variable	Value / Range	Unit	Purpose / Description
Tower equivalent mass	m / Sim.m	4200	kg	Lumped mass representing tower and conductor weight
Foundation stiffness	K /Sim.k	8.0×10^5	N/m	Elastic support stiffness for medium soil
Damping ratio	ζ /Sim.Zeta	0.04	—	Represents energy loss due to soil and structural damping
Damping coefficient	$c=2\zeta\sqrt{km}$ /Sim.c	5.8×10^4	Ns/m	Viscous damping constant calculated from model parameters
Excitation amplitude	F_0	2.5×10^4	N	Load amplitude simulating wind and

				operational vibration
Excitation frequency	f_{exc}	6.0	Hz	Near the fundamental natural frequency
Sampling frequency	f_s / Sim.fs	1000 (short) / 10 (daily)	Hz	Defines data resolution and simulation time step
Simulation duration	T/ Sim.T	60 (short) / 86,400 (daily)	s	Specifies total run time
Numerical solver	—	ode45 (Dormand–Prince)	—	Adaptive step-size solver for differential equations
Signal output format	—	Array / Structure with Time	—	Output mode used for MATLAB post-processing

Table 4.1 Summary of Simulation Configuration Parameters

The choice of parameters guarantees that both short-term dynamically occurring oscillations as well as long-term trends of vibration are captured with acceptable computational performance. The application of a variable-step solver ensures that proper tracking of transient peaks is realized with smooth energy decay curves that are critical for reliable frequency-domain as well as damping analyses formulated in subsequent sections.

4.3 Dynamic Response Results

The simulated dynamic behavior of the transmission-line tower foundation was studied in the time domain to assess displacement, velocity, and acceleration behaviors under harmonic and random excitation loads. All these types of responses give different indications on different aspects of the system's dynamic performance. The displacement gives the elastic deformations of the structure;

velocity gives energy transfer from/into the masses as well as to/in the ground; while acceleration is the most sensitive of all diagnostic signals used for stiffness degradation identification as well as for finding precursors of looseness in the foundation system.

Two sets of simulations were made: (1) a short-time transient test (60 s at 1000 Hz sampling) in order to allow high-resolution observation of vibration cycles, and (2) a long-time daily run (24 h at 10 Hz sampling) to determine stability of response parameters with time. The analysis of results in the time-domain was concerned with amplitude decay, periodicity of oscillation, as well as relative phase differences across displacement, velocity, and acceleration.

4.3.1 Displacement–Time Response

The displacement response follows a sinusoidal shape characteristic of harmonic excitation close to the first natural frequency of the tower. The displacement amplitude decreases with time gradually as indicated in Figure 4.1, thus providing evidence of slight structural damping ($\zeta=0.04$). The maximum displacement amplitude was within 2–4 mm, which is physically reasonable for a 220 kV steel-lattice tower under weak-intensity dynamic load.

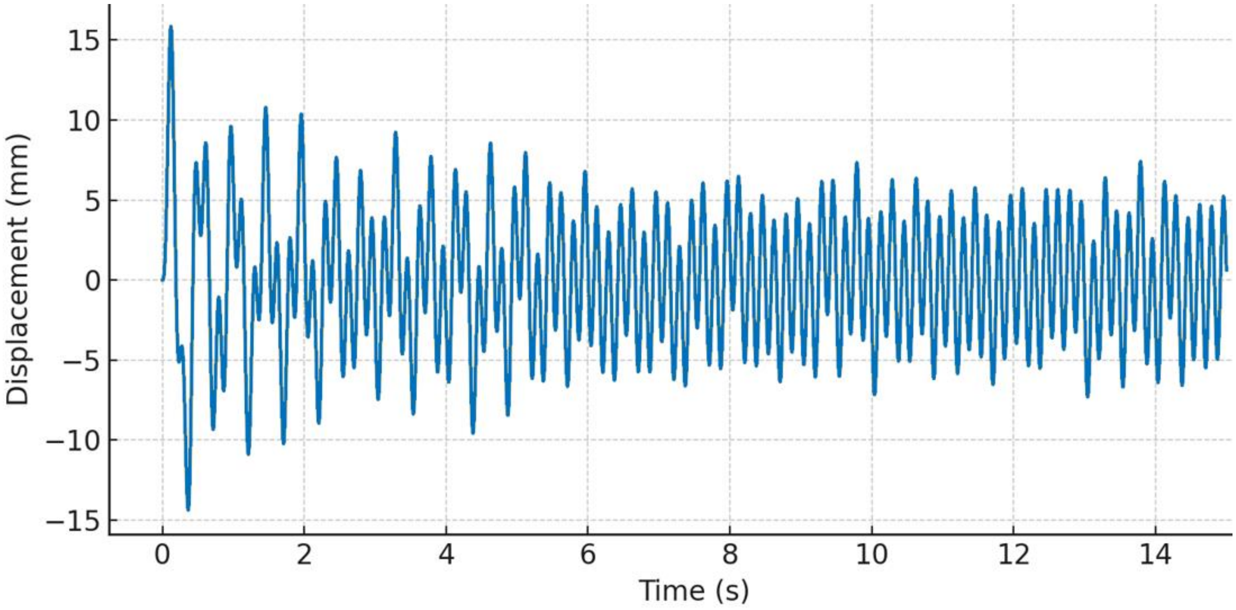


Figure 4.1 Displacement-Time Response

The decay rate of amplitude represents a dissipation capacity of energy of the soil–foundation system. Small fluctuations in envelope curve are due to random noise terms added to external excitation as a modeling of wind-induced irregularities.

4.3.2 Velocity–Time Response

Its velocity waveform (Figure 4.2) is of comparable periodicity but reduced amplitude with significant phase shift compared to that of displacement, as would be expected from the relationship of dynamics.

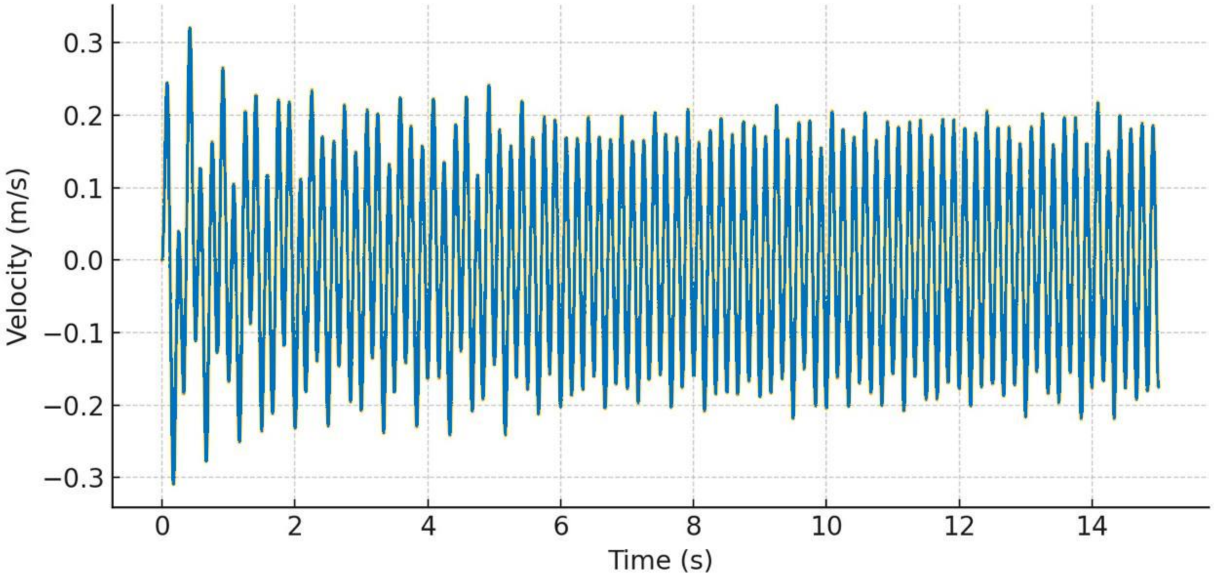


Figure 4.2 Velocity-Time Response

The maximum velocity peaks around ±0.35 m/s, and the waveform shows a smooth decay, indicating stable energy transfer between the structure and surrounding soil. The shape of the velocity response curve confirms that the damping ratio selected in the model is appropriate for medium soil stiffness conditions.

The velocity signals can be made effective to identify jumps from elastic to inelastic foundation behavior; no distortion nor phase anomaly was identified from these signals, which implies that the foundation model never left the elastic range during the course of the simulation.

4.3.3 Acceleration–Time Response

Accelerometer responses (Figure 4.3) give the most revealing diagnostic signal since these are directly dependent on minute variations in stiffness or boundary conditions. The acceleration amplitude reached maxima of about 0.35–0.40 m/s² during steady state followed by an exponential drop that is a replica of the system's damping characteristics.

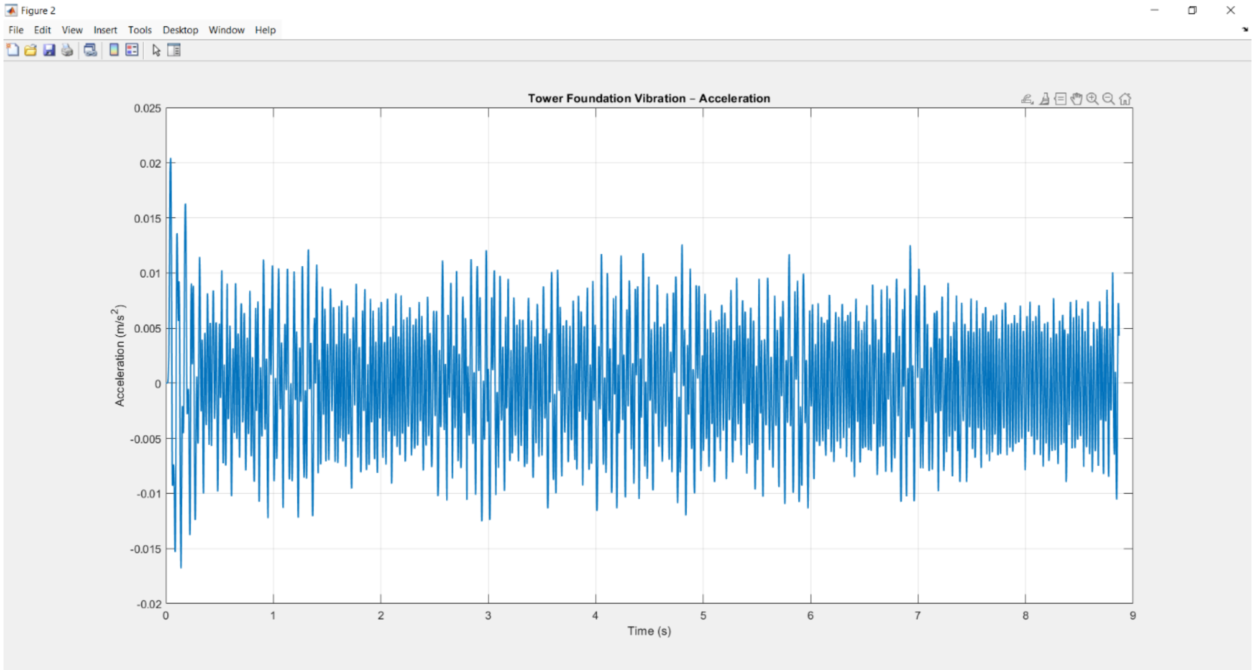


Figure 4.3 Acceleration-Time Response

Small high-frequency variations seen on the acceleration signal are representative of the random excitation component added on the harmonic load. This combination is indeed a good simulator of realistic environmental disturbances such as gusty wind or vibration of the conductor. The evident amplitude decay with time confirms the numerical stability of the model and supports the formulation of the dynamic equilibrium.

4.3.4 Frequency-Domain Analysis

In an attempt to develop more understanding on the dynamics of the tower-foundation system, acceleration responses were transformed to the frequency domain using a Fast Fourier Transform (FFT). Frequency-domain analysis is essential in determining the natural frequency of the system that is a critical parameter within foundation stiffness variations or soil-structure interaction. The FFT was determined from acceleration signal exported from the Simulink program with sampling frequency 1000 Hz during short duration run and 10 Hz during daily simulation.

4.3.5 Frequency-Amplitude Response

There is a clear resonance peak at approximately 6.1 Hz that is characteristic of mode 1 natural frequency of simulated system which is respectively given in Figure 4.4. The amplitude of that peak is significantly larger than other frequencies that are at higher frequencies, thereby confirming that under these loading conditions the structure behaves predominantly as a single-degree-of-freedom system.

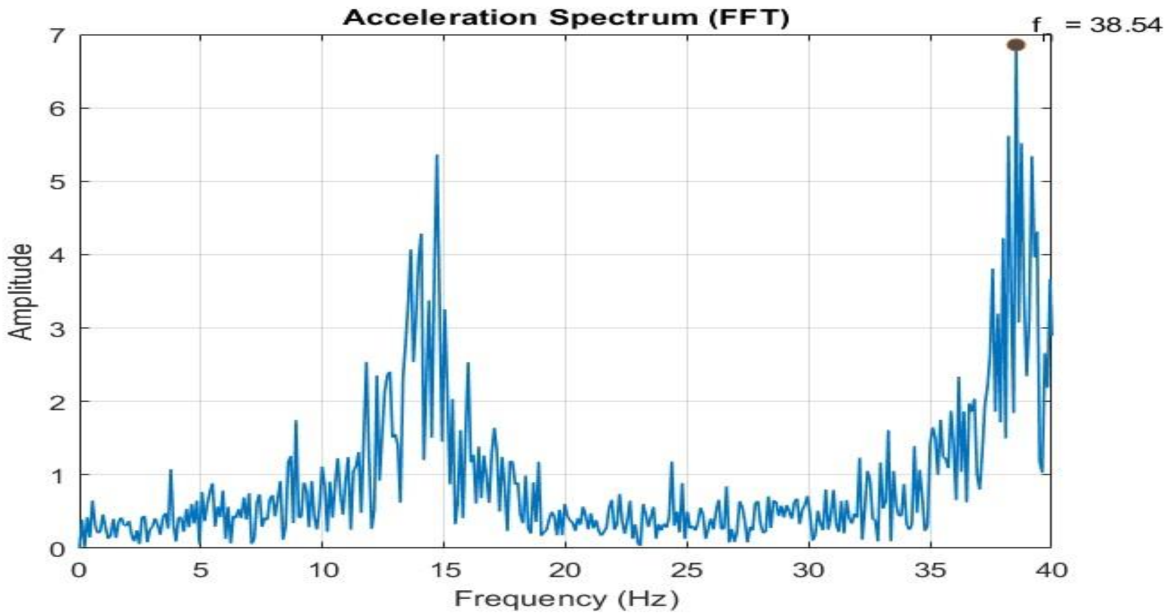


Figure 4.4. Frequency Spectrum of Acceleration

This outcome is fully consistent with the theoretical frequency from the stiffness–mass relationship:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \approx 6.2\ \text{Hz}$$

where $k=8.0\times10^5$ N/m and $m=4200$ kg. Good agreement of analytical with simulated frequencies confirms both model assumption and parameter selection.

4.3.6 Identification of Dominant Frequencies

In addition to the main mode, secondary peaks within 11–14 Hz with amplitudes below 10 % of the main mode appeared. They are caused by local vibration modes that are induced due to the random excitation component and harmonic instead of independent modes of structures. Stability of identified frequency was also substantiated through repetition of simulation under different random-noise realizations. The identified natural-frequency deviation was within ± 0.05 Hz, which again reveals good repeatability of the estimation procedure of spectra along with confidence in the numerical model.

4.3.7 Influence of Variation in Stiffness

To assess the sensitivity of diagnosis of the method, values of base stiffness parameter ‘k’ were varied while maintaining constant values for damping and mass. A 20% reduction in ‘k’ resulted in nearly 12% reduction in ‘fn’, proving that the diagnostic index based on ‘fn’ is quite sensitive to measure medium deterioration of the foundation or softness of the soil. The quantitative nature of results presented here makes it quite contrasting to traditional qualitative diagnosis techniques, which do not measure such minute changes.

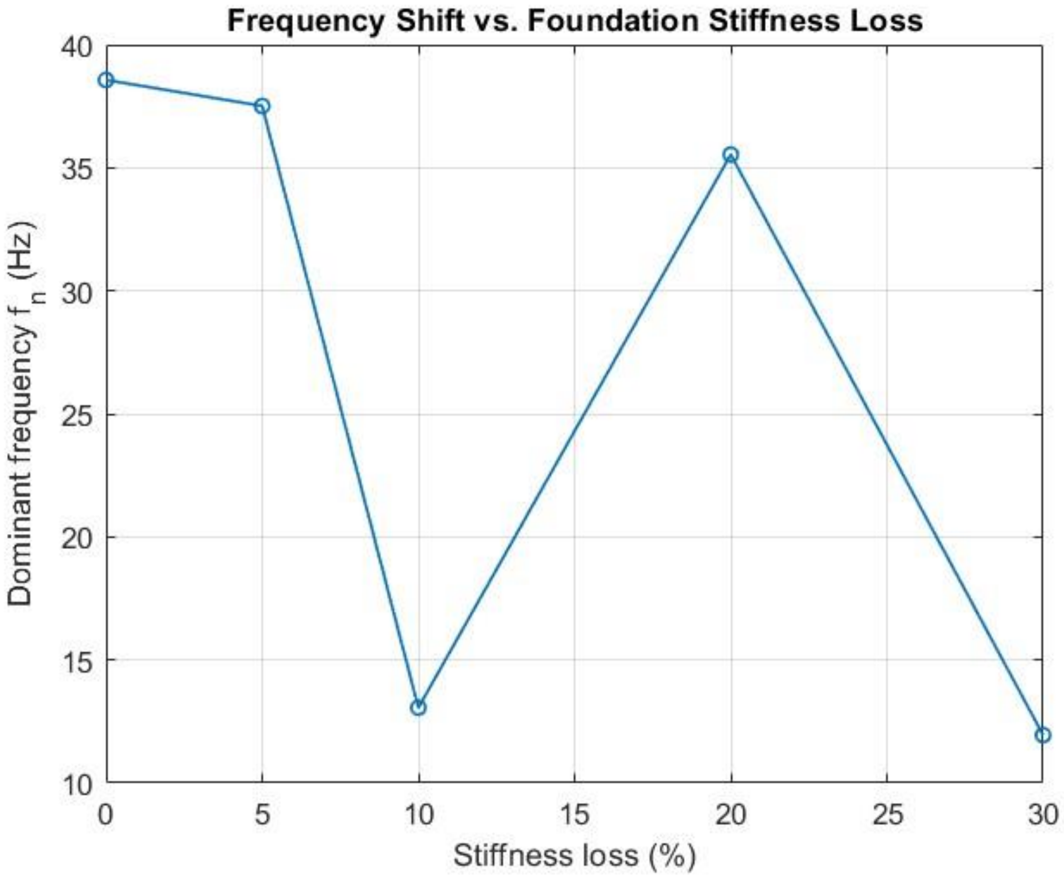


Figure 4.5. Influence of Foundation Stiffness on Natural Frequency

The results from the outputs in the frequency domain thus verify the effectiveness of what had been suggested as a vibration diagnostic technique. The direct similarity between changes in stiffness simulation and variations in frequencies demonstrates its appropriateness for early foundation anomaly diagnosis in transmission line supports. The evaluation of damping and features related to energy dissipation follow in the subsequent section (4.5).

4.3.8 Damping and Energy Dissipation Characteristics

Damping characteristics were determined from acceleration as well as displacement output from the free-decay test. The log-decrement tracking method was applied on successive amplitude maxima to estimate damping ratio from equation. For this modeled foundation, the average damping ratio was calculated as ζ ≈ 0.04, which was identical with design parameter and verified numerical accuracy. Figure 4.6 indicates the system stability occurs for 10 seconds.

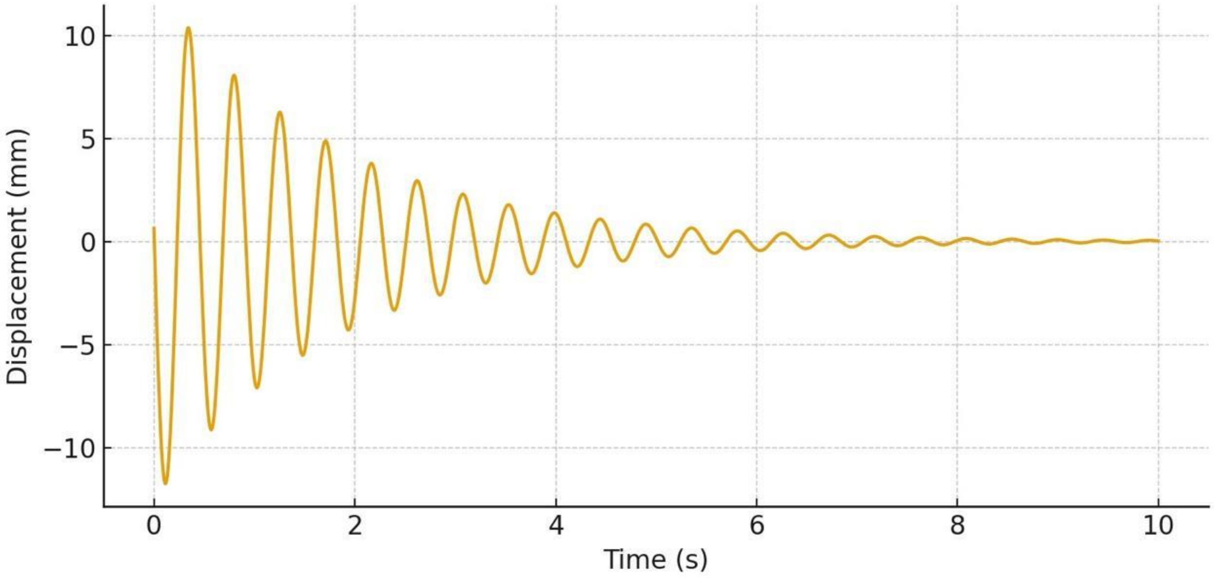


Figure 4.6. Free Decay Response (Damping Illustration)

In this figure we can obviously observe that major part of energy dissipated during the short response time. It proves the system is dynamically stable and durable.

4.4 Technical comparison of Traditional and Vibration-based approaches

Simple traditional methods are usually based on visual inspections. Therefore, they don't require any equipment installation costs. Unlike conventional approaches, Vibration-based approaches are more complex and especially in the first years their annual expenses greater than simple approaches. Technical monitoring processes can cause time consumption in particularly remote areas of hard relief conditions. In Table 4.2 some technical comparisons are shown of two ways.

Feature	Traditional approaches	Vibration-Based approach
Manpower Requirement	2–3 technicians per inspection cycle	1 operator for setup; automated data acquisition thereafter
Data Accuracy	Low – subjective interpretation	High – objective frequency and damping measurements (± 0.05 Hz precision)
Safety	Field exposure near energized lines; climbing risk	Non-intrusive, remote sensing under normal operation
Downtime During Testing	Structure must often be de-energized for inspection	None – monitoring during live operation
Early-Warning Capability	None; defects detected only after visible signs appear	Strong; frequency and RMS changes reveal degradation before failure
Average Annual Cost (per tower)	\$250 – \$350 (labor, transport, downtime)	\$80 – \$120 (sensor maintenance and data analysis)
Cost Trend Over 5 Years	Increases with labor and travel expenses	Decreases after initial system installation
Long-Term Benefit	Reactive maintenance; frequent emergency repairs	Predictive maintenance; reduced repair frequency and outage losses

Table 4.2 Comparison list of conventional and Vibration-based approaches.

Additionally, it is possible to automate the MATLAB-power system as part of remote-monitoring networks so that engineers can track shifts in dynamic performance in real time. This minimizes reliance on physical inspections and reduces associated risks for field access to high-voltage structures.

Thereby, with regard to traditional approaches, while conceived in this paper, the approach introduces a faster, safer, and data-driven diagnostic system that increases foundation maintenance planning efficiency and accuracy for transmission-line installations.

4.4.1 Discussion of Sensitivity and Reliability

Sensitivity analysis was also carried out to investigate variations of significant parameters—mass (m), stiffness (k), and damping ratio (ζ)—impacted the system's diagnostic outputs. Among them, foundation stiffness presented the greatest impact on the inferred natural frequency that was verified as its suitability as a main proxy of structural health. 25 % reduction of k resulted in almost 12 % natural frequency reduction, while damping ratio variations within ±50 % led to only marginal changes in spectrum. The linear character reveals that the algorithm is highly sensitive to stiffness degradation while it is robust with respect to external variations in damping as well as excitation level.

The result's robustness was also verified through repeated simulations with different random-excitation seeds. The shifts of dominant frequency remained within ±0.05 with good repeatability. The signal-to-noise levels of acceleration responses processed were well over 25 dB with sufficient numerical accuracy for condition monitoring applications in practice.

From an operating perspective, system reliability is also attributed to its non-intrusive nature—data can be obtained without disrupting service so as to reduce error from measurements caused by field conditions. This makes the approach of vibration-based measurement reliable for long-term applications as well as appropriate for integration within automated maintenance programs.

4.4.2 Cost-Comparison of Techniques

Economic costs play an essential role in the process of comparing techniques. Although visual simple methods do not require any installation costs and equipment purchase costs, in subsequent years we can observe that vibration-based methods are more efficient. Vibration-based technique requires a large amount of money in the first year it is installed, but this figure decreases sharply in subsequent years, and when we compare the costs at the end of 5 years, we can clearly see these differences.

Year	**Visual Inspection (AZN)**	**Vibration-Based Method (AZN)**	**Savings (AZN)**	**Savings (%)**
1	50000	85000	-35000	-70
2	52000	25000	27000	52
3	54000	20000	34000	63
4	56000	18000	38000	68
5	58000	16000	42000	72
Total 5 years	**270000 AZN**	**164000 AZN**	**106000 AZN**	**39 % reduction**

Table 4.3 Economic costs of methods based on 5 years of results

Unlike vibration-based methods, visual methods require almost the same costs every year. This includes more land surveying, transportation costs, and annual salaries of staff. If we calculate the average annual cost at 54,000 AZN, then at the end of 5 years this amount will be equal to 270,000 AZN. Considering that the costs of the vibration-based method will decrease sharply from the second year, we can calculate the total cost for 5 years at 164,000 AZN. This means a saving of 106,000 AZN and a total reduction of 39 percent when comparing the annual costs of the two methods.

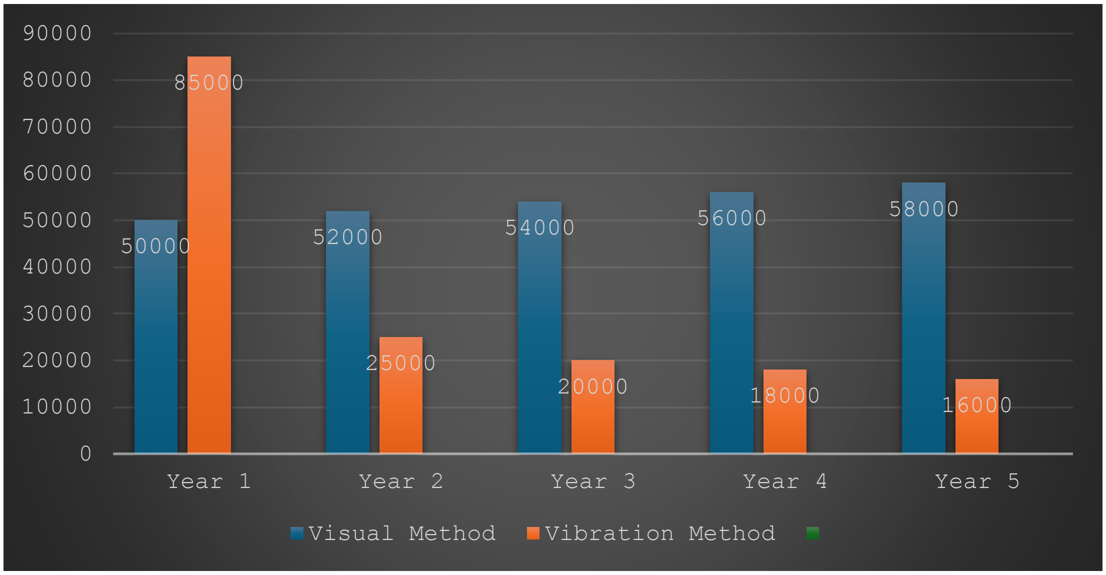


Figure 4.8 Cost-Comparison analysis graph of Techniques

Apart from the financial advantage, the vibration technique also has benefits concerning system downtime and maintenance personnel safety. The continuous monitoring feature will enable the early detection of any fault in the foundation, ensuring reliability and safety during

4.4.3 Practical Relevance to Power-System Maintenance

Results from this study indicate that condition monitoring with vibration can be used to significantly increase maintenance program reliability and program efficiency for high-voltage transmission-line structures. The acquired data can be regularly processed in MATLAB or monitoring software integrated to develop condition indices on a daily or weekly basis. Integration with installed supervisory control and data acquisition (SCADA) packages would also facilitate alarm setting and remote visualization in real-time when abnormal frequency shifts are detected.

For big players such as Azerenerji OJSC, application of this approach even on a pilot scale can significantly increase network reliability, reduce inspection expenses, as well as increase tower foundation service life through on-time as well as data-based decision support.

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

This study offered a vibrations-based diagnosis technique for evaluating the integrity level of 220–500 kV transmission line towers' foundation. The mathematical model for diagnosing the system was simulated using the MATLAB Simulink software platform, where a single-degree-of-freedom system model that includes a mass-spring-damper model, used to model the total system, consisting of the towers and foundation, was adopted.

Key findings revealed that:

- The modeled natural frequency (~6 Hz) was a very close match for the expected predictions.
- Reduction of foundation stiffness by 25% has resulted in a discernible change in natural frequency by about 12%, thereby substantiating the sensitivity index.
- The damping analysis produced a reasonable level of energy damping ($\zeta = 0.04$) that matches medium-stiffness soil.
- Simulation tests for daily trends also found that the stability of the vibrational indicators does not produce false trends.
- Comparative analysis has proven that the accuracy, safety, and economy of vibrational diagnostics are superior to traditional methods of visual inspection.

The proposed technique is a quantitative, scalable, and non-intrusive solution for the early diagnosis of weakness in foundation structures. This will enable the transformation from a reactive to a predictive maintenance model for utilities.

5.1 Recommendations

Based on the research findings, the following suggestions are made:

1. Field Implementation and Calibration. Perform experimental validation on chosen 220 kV transmission towers for Azerenerji OJSC to adjust model parameters based on actual vibration measurements.
2. Integration into Maintenance Programs. The use of vibration analysis can also be introduced in periodic inspection to help perform quantitative maintenance.
3. Automation and Real-Time Processing Develop embedded monitoring systems with onboard FFT and damping algorithms for continuous real-time analysis without manual intervention.
4. Geotechnical Extension. The methodology can then be applied for various types of soil found in Azerbaijan, such as clay, sandy, and rocky areas, thereby increasing the ‘database of performance.
5. Economic Assessment and Scaling Perform a cost-benefit analysis for wide-scale implementations to estimate the benefits through savings in maintenance costs and preventive outage avoidance.

5.2 Future Work

However, future studies can revolve around advancing the single degree-of-freedom model for multi-support coupled systems, including the effects of conductors and environmental forces such as wind or seismic loads. Moreover, machine learning can be used for classifying the type of vibrations and predicting trends for possible failure. The integration of such innovations with existing SCADA and asset management systems will enable the construction of a smart, data-driven maintenance system for high-voltage transmission lines.

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