

Natural Frequency of Buildings and Resonance Phenomenon: Impacts on Structural Design

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ABSTRACT

This piece explores the inherent frequency of buildings and the associated resonance effect, emphasizing their crucial roles in structural engineering. Grasping the natural frequency is vital for forecasting how structures react to dynamic forces such as earthquakes and strong winds. The research underscores the need to take into account the height and weight of buildings, as these elements affect their natural frequency and subsequently influence their performance during seismic activities. Through both theoretical insights and real-world instances including the Mexico City earthquake of 1985 and a building collapse the article illustrates the dangers posed by resonance when a structure's natural frequency coincides with external vibration frequencies. A particular case study is highlighted to demonstrate superior structural and aerodynamic design approaches aimed at reducing resonance due to seismic and wind effects. This study aspires to act as a guide for engineers and architects in recognizing and tackling resonance-related issues to improve the safety and durability of tall buildings.

KEY WORDS: *Natural Frequency, Resonance Effects, Seismic and Wind Response, Structural Dynamics, Structural Failure Analysis.*

NOMENCLATURE

Pa	Modulus Of Elasticity
Hz	Hertz
kg	Kilogram
m ⁴	Moment of Inertia
cps	Cycles Per Second

1.0 INTRODUCTION

In recent times, skyscrapers and elevated structures have gained significance in city settings, enabling higher population concentrations within compact areas. Nonetheless, the

architectural planning of these edifices must take into account the impacts of wind and seismic forces. A structure is deemed tall or high-rise when its height to the smallest width ratio is greater than 5 to 1. Skyscrapers fulfill various functions, such as providing office environments, accommodations, living spaces, and shopping venues. The points below highlight the benefits and drawbacks associated with tall buildings.

1.1 Advantages of Tall Buildings

Tall buildings play a significant role in addressing urban land scarcity by maximizing vertical space. In addition to optimizing land use, these structures offer various economic, environmental, and social advantages. The main advantages are as follows:

1. They optimize land use and support a larger number of occupants compared to shorter structures. Nevertheless, their smaller base makes them more susceptible to vibrations during earthquakes or high winds.
2. The upper levels tend to be more spacious and benefit from increased sunlight exposure. This perk may be compromised during intense lateral shifts due to natural events.
3. Skyscrapers align well with the concept of environmentally friendly architecture since they are better lit, more open, and offer greater space for solar panel installation. Nonetheless, these advantages are coupled with the necessity of maintaining structural integrity, which demands sophisticated engineering to lessen the effects of seismic and wind pressures.
4. They are significantly more cost-effective, as acquiring a small plot of land and erecting a tall structure is generally less expensive than buying a larger area. Still, elevated construction expenses can arise from the need for high-quality materials and innovative structural designs to withstand natural forces.

1.2 Disadvantages of Tall Buildings

Despite their numerous benefits, tall buildings also present several challenges and limitations that must be considered during planning, design, and construction. The main disadvantages are as follows:

1. Designing extremely tall structures requires highly qualified engineers and architects, which raises the overall expenses. This is especially important when considering resistance to earth quakes and wind.
2. Aside from static and dynamic loads, skyscrapers are subjected to wind and seismic forces, making their design more challenging and requiring unique damping

- systems.
3. Skyscrapers surpassing 100 stories encounter oscillation issues, which can lead to shattered windowpanes, as seen in the incident at 200 Clarendon. These oscillations often intensify during strong winds or earthquakes because of resonance effect
 4. The foundations of very tall structures built on limited land experience immense pressure, and soil failure during seismic events can result in the building's collapse
 5. Continuous oscillation can cause discomfort for the building's occupants, underscoring the need for effective vibration control in their design.

One important aspect in the construction of high-rise buildings is the natural frequency, which reflects the building's level of flexibility or stiffness. Natural frequency describes the entire oscillating movement of a structure when no external forces act on it, and it is affected by factors such as height, weight, and inertia. This measurement is usually given in hertz (Hz) or cycles per second (cps). To determine the natural frequency, engineers can use theoretical formulas or software based on the Finite Element Method. There are two primary manual methods for calculating natural frequency: the Single Degree of Freedom (SDOF) approach and the Multi Degree of Freedom (MDOF) approach.

Another important concept is resonance, which takes place when a system or object experiences vibrations that align with its natural frequency. This leads to the object taking in energy and vibrating more strongly, which could possibly cause severe vibrations or even structural collapse.

To prevent resonance, engineers must thoroughly examine the natural frequencies of their designs, ensuring that they are not subject to oscillating forces that match those frequencies. This process might include using different materials, changing the shape of the structure, or incorporating dampers to absorb energy and minimize vibrations.

Grasping the concepts of natural frequency and resonance is essential for enhancing building designs that can endure earthquakes. This study is particularly vital in regions susceptible to seismic activity, since inadequate design may result in major collapses. Urban areas such as San Francisco and Tokyo have felt the impact of earthquakes on high-rise structures, underscoring the importance of thorough evaluation and creative design strategies to mitigate these structures.

2.0 METHOD

The Single Degree of Freedom (SDOF) method is a fundamental analytical approach used to model and analyze the dynamic response of structural systems under various loading conditions. This simplified method provides valuable insight into structural behavior, particularly in seismic and vibration analysis.

2.1 Method Addresses Structures with a Single Degree of Freedom

This approach deals with systems that possess one degree of freedom. Typically, continuous systems have countless degrees of freedom; however, a one degree of freedom model can apply to straightforward buildings that primarily function as a whole.

Figure (1) shows instances of structures that can be depicted as one-degree-of-freedom models for dynamic assessment.

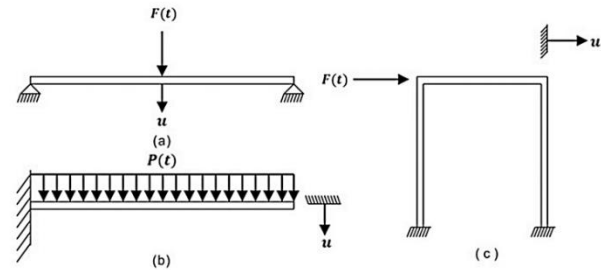


Figure 1: Examples of Structures Modelled as One Degree of Freedom System

The natural frequency in SDOF method is calculated using equation (1) that incorporate the building's mass and stiffness, where the stiffness influences the natural frequency based on boundary conditions (type of supports at each end) and applied loads (uniform load, concentrated load, etc.) figure (1) provides examples for calculating stiffness in various scenarios.

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{m}} \quad \text{Hz}$$

Table 1: Examples for Calculating Stiffness

Boundary Condition and Loading	Stiffness (K)
	$K = \frac{3EI}{L^3}$
	$K = \frac{48EI}{L^3}$
	$K = \frac{12EI}{L^3}$

Where; E is the modulus of elasticity [Pa] I is the moment of inertia [m⁴] m is the mass of the whole building [kg] L is the height of the building [m].

2.2 The Multi Degree Of Freedom (MDOF) Method

The MDOF method is suitable for multi-store structures, such as the frame shown in Figure (2). This approach simplifies the Multi-Degree of Freedom (MDOF) method by approximating it using the Single Degree of Freedom (SDOF) system. The MDOF method typically requires matrix analysis, but in this case, to facilitate the calculation of the natural frequency, we approximate the structure as a simplified system with a total mass (m_{tot}) and an equivalent stiffness (K_{eq}), which allows for a similar approach to SDOF.

In this method, the total mass (m_{tot}) is calculated as the sum of the masses for each floor, as shown in equation (2). The equivalent stiffness (K_{eq}) for the entire structure is determined using equation (3), while the stiffness for each column can be individually calculated by equation (4). The natural frequency is then obtained through equation (5) [7].

$$K = \frac{12 EI}{l^3}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{K_{eq}}{m_{tot}}} \quad \text{Hz}$$

$$m_{tot} = m_1 + m_2 + m_3$$

$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3}$$

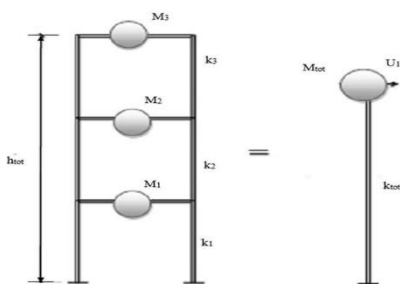


Figure 2: Multi-store Frame and Its Equivalent Single Degree of Freedom System

A. Dynamic Analysis Using Finite Element Method (FEM)

The Finite Element Method (FEM) is a numerical approach commonly used in software such as ANSYS to evaluate the natural frequencies of structures. In this method, the structure is divided into small finite elements, and dynamic equations are formulated for each element, allowing accurate determination of the overall natural frequencies.

Finite Element Method (FEM) is highly precise and enables the examination of complex factors, including material variations and dynamic forces, making it particularly suitable for analyzing complex structures that are difficult to represent using SDOF or MDOF approaches.

1. EXPERIMENTAL MODAL ANALYSIS

Experimental Modal Analysis (EMA) is a practical technique used to identify the natural frequencies of real structures by applying vibrations and measuring their responses. Instruments

such as accelerometers are employed to capture these vibrations, providing precise data on the actual dynamic behavior of the structure. This method is often applied to validate numerical and theoretical results, especially in cases where computer models may not fully represent real-world performance.

2. Choosing The Appropriate Analytical Method

The selection of an appropriate method for calculating natural frequency depends on the structure's complexity and the desired level of accuracy. Designers should select the calculation method based on structural characteristics and project requirements:

A. Use The SDOF Method

Appropriate for uncomplicated, small frame works with a distinct single degree of freedom, where mass and rigidity can be clearly identified. This approach is effective and offers a fast estimation. The subsequent criteria should be satisfied to utilize this method on a structure:

1. Structure must behave like a single mass-spring system.
2. The mass of the structure should be concentrated at a single point.
3. Suitable for simple structures with a dominant mode of vibration.

B. Use The SDOF Method

Ideal for tall structures where each level possesses unique weight and rigidity. This approach is essential for buildings that have several points of movement in order to obtain precise outcomes for the response of each level. To apply this method successfully, the building must meet the subsequent conditions:

1. Structure should have multiple masses and stiffnesses.
2. Suitable for more complex structures with multiple degrees of freedom.
3. Necessary when the interaction between masses and degrees of freedom is significant.

C. Dynamic Analysis Using Fem

Essential for irregular or high-rise constructions, complex geometries, or structures requiring strict performance standards, the Finite Element Method (FEM) provides exceptional precision despite being time-consuming. It is particularly advantageous in the final stages of design or when validation through experimental testing is needed. However, for this method to be implemented successfully, the structure must satisfy specific criteria:

1. Structure must be discretized into finite elements.
2. Suitable for structures with complex geometries and material properties.
3. Necessary when detailed stress, strain, and deformation results are required.

By thoughtfully evaluating these alternatives, designers can choose a technique that corresponds with the complexity of the structure, its height, and the current stage of the project, ensuring a good balance between precision and effectiveness.

The height of a structure greatly affects its natural frequency; with an increase in height, the natural frequency usually decreases. This change results in varying natural frequencies for tall, average, and short

buildings. When a structure experiences dynamic forces like those from wind or seismic activity, it vibrates at a particular frequency. If this vibration frequency is very close to the natural frequency of the building, resonance may take place, which can potentially cause significant damage to the structure. The next section will explore the phenomenon of resonance in more detail.

4.0 RESULT

1. Study of Modern Seismic Isolation Technologies:

Future research could focus on the impact of advanced technologies such as smart materials or active isolation systems in reducing the effects of earthquakes on structures.

2. Expanding Studies to Different Types of Buildings:

Future research can look into the effect of seismic isolation on different types of structures, such as residential, cultural, or ancient buildings.

3. Impact of Environmental and Climatic Factors:

Research could examine how environmental changes, such as temperature and humidity, influence the properties and effectiveness of seismic isolation materials.

4. Digital Seismic Simulation Models:

Researchers could develop advanced simulation techniques to better model seismic events and their impact on various types of buildings.

5. Effects of Earthquakes on Historic Structures:

Further work can focus on the effects of earthquakes on ancient monuments and the development of preservation methods to protect cultural heritage.

6. Seismic Isolation and Building Sustainability:

Research could explore how seismic isolation contributes to the long-term sustainability of buildings, reducing maintenance costs and enhancing their longevity.

7. Experimental Validation of Computational Models:

Practical experiments on different seismic isolation systems could be conducted to validate and improve computational models, providing real-world data for more accurate predictions.

4.0 CONCLUSION

This review highlights key insights about the natural frequency of buildings and the resonance phenomenon. The following points summarize the main findings:

1. Natural Frequency as a Key Factor:

The natural frequency is a critical indicator of a building's flexibility or rigidity and plays a significant role in the design of tall structures.

2. Definition of Tall Buildings:

A building is classified as tall or high-rise if its aspect ratio (height to the smallest lateral dimension) exceeds 5:1.

3. Impact of Earthquake Frequency on Building Height:

According to the BOSS model, high-frequency earthquakes primarily affect low-rise buildings, while low-frequency earthquakes have a greater impact on tall structures.

4. Resonance and Building Response:

When the natural frequency of a building matches the frequency of ground motion, the building will experience the largest possible displacement and may suffer significant structural damage. This phenomenon is known as resonance.

5. Historical Example of Resonance Effect:

The collapse of the Tacoma Narrows Bridge in 1940 is a notable example of structural failure due to resonance effects.

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