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Investigation of the Dynamic Behavior of a Chimney at Tripoli-West Power Plant

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Abstract

This paper investigates the vibration behavior of a chimney at the Tripoli-West power plant under wind loads. Finite element models of the chimney are developed to analyze the existing chimney structure, and assess the impact of repositioning the supporting rings typically used in such chimneys. Both free vibration modal analysis and forced vibration harmonic analysis are performed using ANSYS software, considering the wind loads in the area. The final recommendations focus on the vibration response and the influence of the supporting rings and their locations along the chimney, aiming to mitigate undesired vibrations and structural fatigue problems.

Keywords: Structural vibration, Industrial chimneys, Finite Element Analysis (FEA).

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دراسة السلوك الديناميكي لمدخنة في محطة توليد كهرباء طرابلس-الغرب

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الملخص

تبحث هذه الورقة في سلوك الاهتزاز لمدخنة في محطة توليد الكهرباء طرابلس-الغرب تحت تأثير الرياح. تم بناء نماذج العناصر المحدودة للمدخنة، وتحليل الهيكل الحالي، ثم دراسة تأثير تغيير مواضع الحلقات الداعمة التي تستخدم عادة في مداخن من هذا النوع. تم إجراء تحليل الاهتزاز الحر باستخدام برنامج المحاكاة أنسيس (ANSYS)، وكذلك تحليل الاهتزاز القسري باعتبار الأحمال الناجمة من الرياح في المنطقة. انتهت هذه الدراسة الى تسليط الضوء، كتوصيات نهائية على استجابة المدخنة على شكل اهتزازات ناجمة عن الرياح، وكذلك على تأثير الحلقات الداعمة ومواقعها على طول المدخنة من أجل التغلب على مشاكل الاهتزازات غير المرغوب فيها والتقليل منها وبالتالي تقليل الإجهادات المرتفعة الواقعة على هيكل المدخنة.

الكلمات المفتاحية: الاهتزازات الانشائية، المداخن الصناعية، طريقة تحليل العناصر المحدودة.

Introduction

Industrial chimneys are subjected to various wind loads, load value and direction, and thus would vibrate under the action of wind. These oscillations are due to the vortices that appear and disappear at regular time intervals on opposite sides of the chimney. When the excitation frequency of the wind load is close to the natural frequency of the chimney, the vibration will reach an amplitude that may cause fatigue failure. One way to overcome unwanted vibrations is to increase damping in the chimney base structure by using an elastic foundation.

Many researchers have evaluated the effect of deterministic wind loads on the dynamic response of chimney [1, 2, 3, 4]. The effect of wind stretching on Reinforced Concrete Chimneys (RCC) on tall chimney, 150m high, has been investigated by Karan [5] and Singh [6]. In this study, the wind speed at 145m of height was not

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measured but rather estimated. Niemann et al. [7] investigated the vibration modeling of chimneys under wind loads. Two different models were studied in this paper regarding the design for vortex resonance. One was Ruscheweyh's approach, while the other was based on Vickery & Basu's model of self-limiting response process. The results showed that a beam model is neither realistic nor on the safe side. Rather, they recommended that a shell model has to be applied, and pressures have to be utilized as forces rather than wind loads. The influence of using supporting rings along a chimney on its static behavior was studied by John et al. [8]. A miniature model of the chimney was made using fiber-reinforced plastic with a geometric scale of 1:150 representing a chimney with a height of 100m to illustrate the importance of wind interference between different buildings of the power station. It was also proven, through an experimental model, that using supporting rings in the upper two-thirds region of the chimney reduces the mechanical stresses and deflections. Reddy et al. [9] reviewed the along and across wind effects on a chimney, considering two regions with different wind speeds. The effect of vortex shedding on the chimney structure was also investigated. It was found that the across-wind calculation is directly proportional to the weight of the chimney, frequency, and mode shapes, but not to wind speed, such that across wind load is not increasing with the increasing wind speed. Other research works, such as Babu et al. [10] and Baiju & Geethu [11], have studied the dynamic behavior of tall chimneys, stress profile change due to wind load, the influence of a long-wind and across-wind on the static and dynamic behavior of chimneys, and wind influence on the lateral deflection of top of the chimney, using few ANSYS models.

It should be mentioned that no other investigation has been conducted before regarding the dynamic analysis of the chimney located at the Tripoli-West power plant. This study is concerned with the dynamic analysis of this self-supporting reinforced concrete chimney, studying the dynamic behavior of chimney at its top, the influence of using supporting rings along its length, and the locations of these rings along the chimney. Detailed data on the geometrical and material parameters of the chimney has been collected. Some dimensions were not available and have been measured on site. A finite element model was built utilizing SolidWorks and ANSYS platforms to study the influence of the aforementioned parameters.

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Description of Chimney

The Tripoli-West power plant is located ~15 Km west of Tripoli, situated on the seashore of Janzour. The chimney is part of a steam power plant generating 120MW, with an amount of gas flowing of about 400 m^3 /s, at a temperature ranging from 40 ^oC to 110 ^oC. The chimney body consists of reinforced concrete and bricks for heat isolation, Figure 1.

Figure 1. The Investigated Chimney at Tripoli-West Power Plant

The dimensions of the chimney are as follows:

- Height of the chimney: 105 m
- Thickness of the reinforced concrete: 0.4m
- Gap between brick and wall: 0.1m
- Thickness of the brick: 0.4m
- Outer diameter at the bottom: 9.3m
- Outer diameter at top: 5m
- ½ of taper angle: 1.173 ^{o}

The materials parameters used in modeling are defined by bricks modulus of elasticity =11.146 GPa, bricks Poisson's ratio=0.156, bricks mass density=2000 kg/m^3. Steel modulus of elasticity=200 GPa, Steel Poisson's ratio=0.3, Steel mass density=7900 kg/m^3. The reinforced concrete parameters are calculated as follows ([12] and [13]):

$$E_{R.C.C} = \frac{(E_S A_S)+(E_C A_C)}{(A_S+A_C)} \quad (1)$$

$$\nu_{R.C.C} = \nu_s V_S + \nu_C V_C \quad (2)$$

$$\rho_{R.C.C} = \rho_s V_S + \rho_C V_C \quad (3)$$

Where: E_{RCC} is Young's modulus of reinforced concrete, E_S and E_C are Young's modulus of steel and concrete, respectively, A_S and $A_C$are the area fraction of steel and concrete, and V_S and V_C are the volume fraction of steel and concrete, respectively. In the same manner, Poisson's ratio ν_{RCC} and mass density ρ_{RCC} of the reinforced concrete are calculated. Thus, using these formulas, the reinforced concrete mass density is calculated to be 5320 kg/m^3 , its Poisson's ratio equal to 0.21, and Young's modulus equal to 107 GPa.

Wind Load Calculations

Chimneys experience major loads coming from the wind from all directions and have different loads at different heights. The wind loads can be of two kinds; quasi-static load, which is the force acting on the chimney, calculated as time-averaged steady speed, and dynamic load generated because of gust and vortex shedding. The wind acting on the chimney in our case is considered the along wind type, which is the wind acting directly on the surface of the chimney. As the wind speed changes according to many factors, mainly the height, and the design wind speed can be calculated as a function of a few parameters, according to [14],

$$\mathrm{V_Z} = \mathrm{V_b K_1 K_2 K_3} \quad (4)$$

Where: V_Z is the design wind speed at any height, V_b is the basic wind speed at any height, K_1 is the probability factor (risk coefficient), K_2 is the terrain, height, and structure size factor, and K_3 is the topography factor. The wind-induced forces acting on the chimney depend on many parameters such as the shape and direction of wind incident on the chimney surface, chimney height, influence of nearby structures, and the properties of the chimney itself. However, for simplicity, it becomes convenient to consider equivalent static forces. The static force acting on the chimney, usually called drag force, creates along-wind shear forces and bending moments. The drag force acting on a body is calculated as [15],

$$F_D = \frac{1}{2}\rho_a v^2 C_D\, A \tag{5}$$

Where: F_D is the drag, ρ_a is the density of air, C_D is the drag coefficient that depends on Raynold's number Re, shape, and aspect ratio of the structure, and A is the cross-sectional area normal to wind direction. The gust effect, due to fluctuations of wind speed, is neglected and an average wind speed is assumed to act. In addition, the flow state of air is considered laminar, Re<5.

Wind Speed Profile

In order to collect wind speed data in the city of Tripoli, the Libyan National Meteorological Centre, and the Department of Climate Management and Climate Change were visited to acquire the necessary data. These data are the average wind speed and the maximum wind speed measured at 10 m above sea level near the main seaport of Tripoli. The data collected covers the period from 1993 to 2009. The average wind speed in a certain month was calculated by taking the average over all days of the month, and the maximum wind speed is the highest recorded reading obtained for each month. It was observed from the data that the maximum occurred during the year 2001, as shown in Figure 2. This was our basic wind speed used in this analysis.

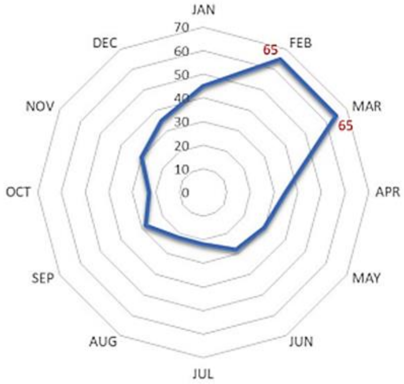

Figure 2. Maximum Observed Wind Speed during the Year 2001

The maximum values of wind speed were observed in the year 2001, about 65 knots (33.44 m/s), which is the basic wind speed V_b. The parameters K_1 and K_3 depend on the class of structure and wind speed. They were fixed at the values of 1.06 and 1.0 respectively, as in [16]. The parameter K_2 changes according to different categories

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of terrains and it varies with height. For our case, K_2 changes according to height, and accordingly the design wind speed also changes, as shown in Figure 3.

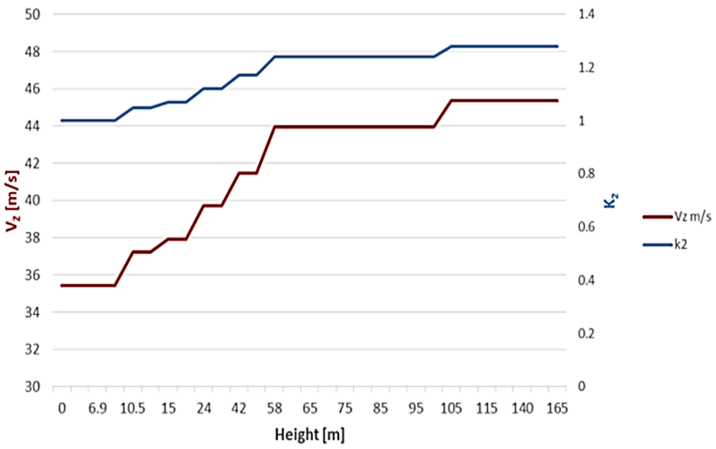

Figure 3. The Change of the Design Wind Speed V_Z and the Parameter K_2 with Chimney Height

To estimate the design wind speed for any given height, these data were curve-fitted using MS-Excel resulting in the following second order polynomial, with **h** being the height,

$$V_Z = -0.0007h^2 + 0.164h + 35.252 \qquad (6)$$

This equation is used in the model to specify the wind load acting on the chimney according to its height.

Modeling the Chimney

A finite elements model was created in SolidWorks® and ANSYS software to investigate the effect of wind on the chimney. Dynamic analysis is performed, in which the physical chimney model is divided into several elements, each with a specified number of nodal points, and the problem is mathematically summarized into a huge global system in the form,

$$([K] - \omega^2[M])\{x\} = \{F(t)\} \qquad (7)$$

Where: $[K]$ is the structural stiffness matrix, $[M]$ is the structural mass matrix, and $\{F\}$ is the applied load.

The investigation consists of three models for chimney. Model 1 is referred to the existing chimney on site. Model 2 and Model 3 are

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proposed in this study to investigate the effect of surrounding rings on the dynamic characteristic of the chimney.

- **Model 1: the existing (original) chimney on site**

The original chimney (Model 1) is modeled in a way that it is fixed to the ground at the bottom, at its base. A mesh consisting of a total of 5523 triangular solid elements and a total of 12821 nodes is used, as shown in Figure 4. This mesh was sufficient for the solution convergence, as tested by ANSYS itself. The obtained results for the first three modes of oscillation of this model are shown in Figure 5.

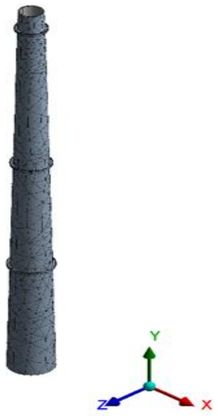

Figure 4. Finite Element Mesh of Model 1: the Original Chimney

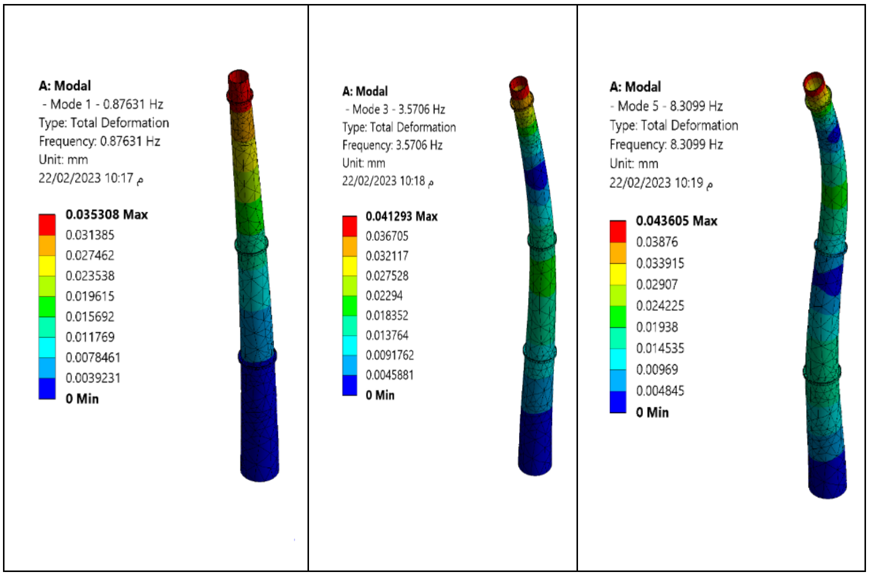

Figure 5. First Three Bending Modes of Model 1

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- **Model 2: No-rings model**

In Model 2, the three rings surrounding the original structure of chimney on three different levels were removed from the model. This was done to investigate the effects of these rings on the dynamic behavior of the chimney. A new model was built using a suitable mesh for solution convergence, and the model was solved. The resulting dynamic behavior of chimney is shown in Figure 6.

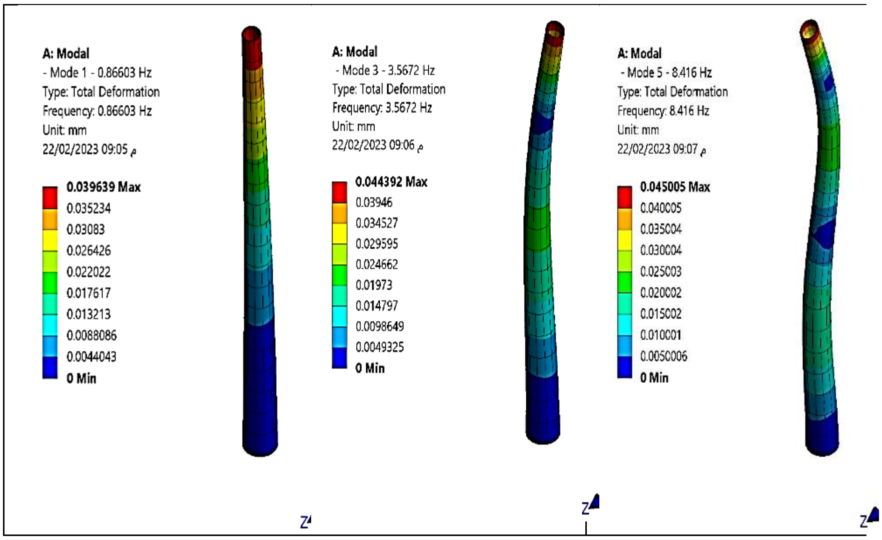

Figure 6. First Three Bending Modes of Model 2

Observe that, in this case, the natural frequencies slightly decreased compared with the original model.

- **Model 3: Rearranged position of rings**

The use of the rings is important, used as “stitches” for possibly generated cracks, as structure supporters or fasteners, or needed for maintenance purposes. With that in mind, the positioning of the rings would have an effect on the dynamic behavior of the chimney. For that, Model 3 with rearranged positioning of the rings was performed. In this model, the rings are positioned in an equally-spaced pattern, in the upper 1/3 part of the structure. Again, a finite element model was built with a sufficient number of nodes, and solved. The obtained results for the first three bending modes of oscillation of this model are shown in Figure 7.

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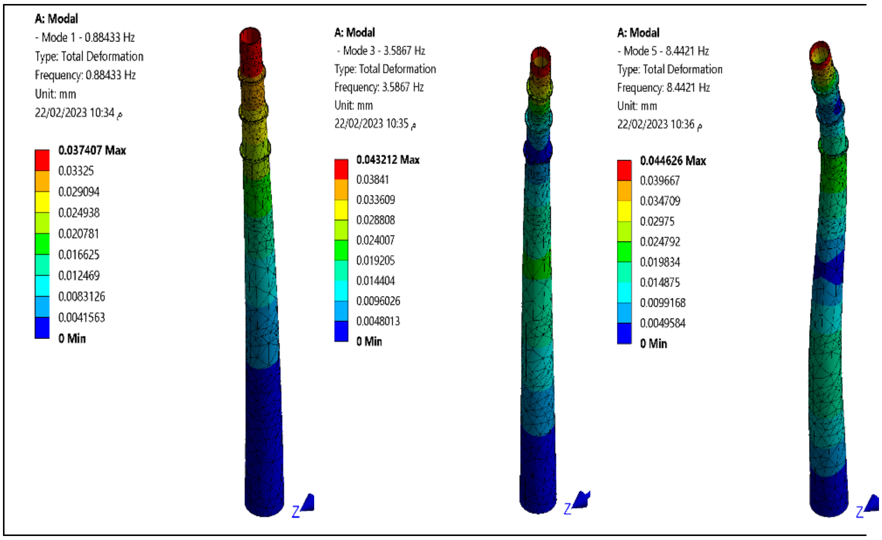

Figure 7. First Three Bending Modes of Model 3

Comparison of the Three Models

The comparison between the three models for significant modes of oscillation is listed in table 1. Bear in mind that, due to the wind loading, the most important mode shapes in these cases are the bending modes. Nevertheless, twisting mode shapes are observed especially in the case where no rings are used.

Table 1. Comparison between the Existing Chimney Structure and Other Two Investigated Models.

Comparison of Natural Frequencies						
Mode No.	Model 1 (Original chimney)		Model 2 (No Rings)		Model 3 (Rings on upper 1/3 part)	
	Frequency (Hz)	Mode type	Frequency (Hz)	Mode type	Frequency (Hz)	Mode type
1	0.87631	bending	0.86603	bending	0.88433	bending
3	3.5706	bending	3.5672	bending	3.5867	bending
5	8.3099	bending	8.416	bending	8.4421	bending
7	12.195	bending	10.024	Twisting	11.258	Twisting
8	12.494	Twisting	12.678	bending	12.498	bending
9	14.747	bending	14.867	bending	14.866	bending

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Based on the obtained results of model 3, one can see that the dynamic behavior of the chimney is slightly improved.The comparison between the three models for 20 modes of oscillation is shown in Figure 8. As a result, the rings have an effect on the dynamic behavior.

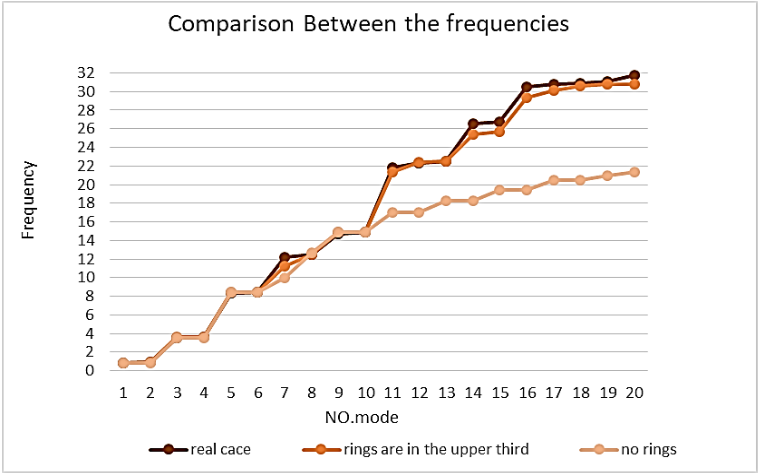

Figure 8. Comparison between the Three Models

Harmonic response analysis was conducted in ANSYS to determine the chimney response to wind force. A unit force is applied at the top of the chimney, and the harmonic response is calculated at the same position. This analysis was performed for the three models under investigation. Figures 9, 10 and 11 display the frequency response function (FRF) for each model, respectively.

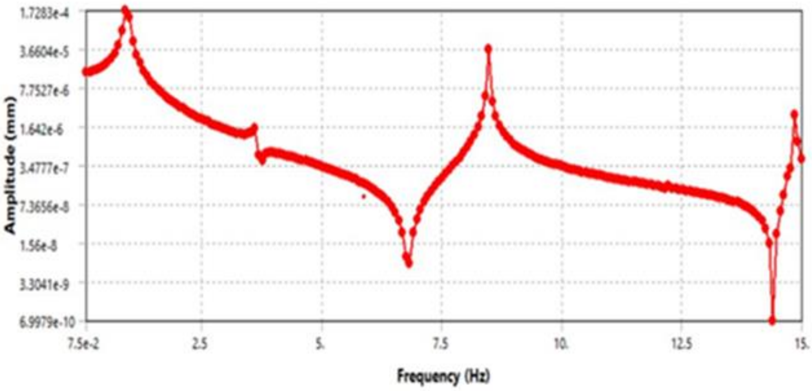

Figure 9. Frequency Response Function of Original Chimney (Model 1)

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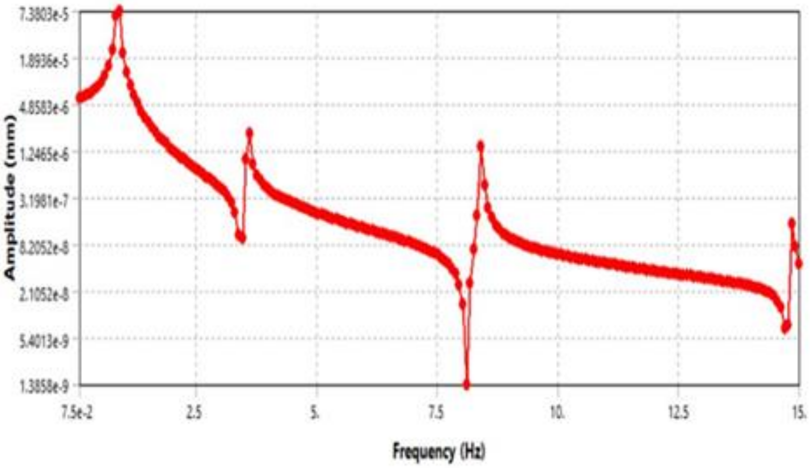

Figure 10. Frequency Response Function of No-Rings Chimney (Model 2)

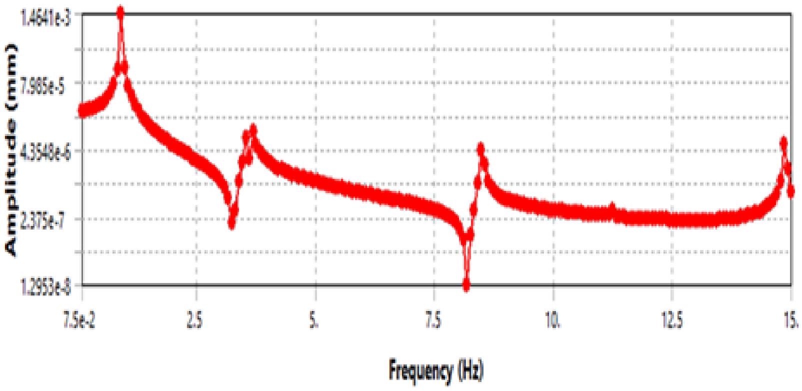

Figure 11. Frequency Response Function of Chimney With Rearranged Rings (Model 3)

Although the FRFs appear quite similar, there is a slight variation in the calculated natural frequencies, as shown in Table 1, for the first 10 mode shapes. Beyond the 10th mode shape, the influence of the rings becomes noticeable, making the chimney's dynamic behavior sensitive to the positioning of the three rings.

Conclusions

The impact of wind on a self-supporting reinforced concrete chimney at the Tripoli-West power plant is analyzed numerically using finite element analysis. The dynamic behavior of the original

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chimney structure is examined in situ. Additionally, two alternative models are proposed to evaluate the influence of the three rings surrounding the original chimney on its dynamic characteristics. The findings indicate that the dynamic behavior of the chimney can be enhanced by altering the distribution of the rings along the chimney body. The addition of rings introduces concentrated masses that affect the natural frequencies. The natural frequencies for the investigated cases appear quite similar for the first 10 mode shapes, with slight variations. But beyond the 10th mode shape, the influence of the rings becomes noticeable, making the dynamic behavior of the chimney quite sensitive to the positioning of the three rings.

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