عدد خاص بالمؤتمر الليبي الدولي للعلوم التطبيقية والهندسية دورته الثانية (II)
2024 / 10 / 30-29
https://orcid.org/0009-0009-5409-692

تم استلام الورقة بتاريخ:8/ /2024م وتم نشرها على الموقع بتاريخ: 30/ 10/2024م

Diagnosis of High Vibration Causes at the Screw Air Compressor Base Frame in Souq Al-Khamis Cement Factory (Part I)

http://www.doi.org/10.62341/aosf2111

Ahmed Omran[1,2], Osama Hassin[1]*, Sadok Sassi[3], Fengshou Gu[4]

1 Libyan Academy for Postgraduate Studies, Libya
2 Mechanical Engineer in Souq Al-Khamis cement factory, Ahlia Cement Company, Libya
3 Qatar University, Qatar
4 University of Huddersfield, UK

*Osama.hassin@academy,edu,ly

Abstract

This paper investigates the resonance phenomenon and modal characteristics of a screw air compressor base frame in the cement manufacturing industry. Numerical analysis and data comparison techniques were used to identify and analyze the resonance issue in a specific compressor at Souq Al-Khamis Cement Factory. The research begins by studying the natural frequencies and mode shapes of the compressor base frame through Finite Element Method (FEM) using the ANSYS Workbench. Practical measurements are conducted using the PHYPHOX App Vibration Analyzer to obtain vibration data from the compressor. The findings of this study contribute to understanding the resonance phenomenon in screw air compressors and provide valuable insights for improving the design and maintenance of compressor base frames in the cement manufacturing industry. By identifying the relationship between excitation frequencies and natural frequencies, measures can be taken to mitigate resonance-related vibration problems and ensure the reliable operation of cement production equipment.

Keywords: Vibration resonance, Base frame of screw air compressor, Mode shapes, Natural frequencies, Numerical analysis (FEM).

عدد خاص بالمؤتمرالليبي الدولي للعلوم التطبيقية والهندسية دورته الثانية (II)
2024 / 10 / 30-29
https://orcid.org/0009-0009-5409-692

تم استلام الورقة بتاريخ:8/ /2024م وتم نشرها على الموقع بتاريخ: 30/ 2024/10م

تشخيص أسباب الاهتزازات العالية في إطار قاعدة ضاغط الهواء اللولبي بمصنع أسمنت سوق الخميس (الجزء الأول)

م. احمد عمران[1,2]، د.أسامة حسين[1*] ، أ.د. صادق ساسي[3] ، أ.د. فنق قو[4]

[1] الاكاديمية الليبية للدراسات العليا، طرابلس، ليبيا

[2] الشركة الاهلية لصناعة الاسمنت / سوق الخميس ، ليبيا

[3] جامعة قطر ، قطر

[4] جامعة هيدرسفيلد، بريطانيا

osama.hassin@academy,edu,ly

الملخص

تبحث هذه الورقة في ظاهرة الرنين والخصائص المشروطة لإطار قاعدة ضاغط الهواء اللولبي في صناعة تصنيع الأسمنت. تم استخدام تقنيات التحليل العددي ومقارنة البيانات لتحديد وتحليل مشكلة الرنين في قاعدة ضاغط معين في مصنع أسمنت سوق الخميس. يبدأ البحث بدراسة الترددات الطبيعية وأشكال الوضع لإطار قاعدة الضاغط من خلال طريقة العناصر المتناهية الصغر باستخدام انسس وركبنش. يتم إجراء القياسات العملية باستخدام تطبيق الاهتزاز فويفوكس للحصول على بيانات الاهتزاز من الضاغط. تساهم نتائج هذه الدراسة في فهم ظاهرة الرنين في ضواغط الهواء اللولبية وتوفر رؤى قيمة لتحسين تصميم وصيانة إطارات قاعدة الضاغط في مصنع الأسمنت. من خلال تحديد العلاقة بين ترددات الإثارة والترددات الطبيعية ، يمكن اتخاذ تدابير للتخفيف من مشاكل الاهتزاز المتعلقة بالرنين.

الكلمات المفتاحية: رنين الاهتزاز، الإطار الأساسي لضاغط الهواء الحلزوني، أشكال الأوضاع، الترددات الطبيعية، التحليل العددي

عدد خاص بالمؤتمرالليبي الدولي للعلوم
التطبيقية والهندسية دورته الثانية (II)
2024 / 10 / 30-29
https://orcid.org/0009-0009-5409-692
تم استلام الورقة بتاريخ:8/ /2024م وتم نشرها على الموقع بتاريخ: 30/ 10/2024م

1. Introduction

In the cement industry, rotating machines are frequently used to transfer liquids, gases, cement, and other goods. The Souq Al-Khamis Cement Factory uses a screw air compressor to move cement from the mill to storage silos. Understanding the various types of air compressors is essential because they are used in various industries, including manufacturing, building, and others. Furthermore, the compressor's basic frame structure is essential for supporting, safeguarding, and sustaining the normal function of its components. As the implementation result of Condition-Based Maintenance (CBM) significantly enhances overall equipment reliability and maintenance strategies across various industrial sectors. In the oil and gas industry, for instance, CBM facilitates real-time monitoring and data analysis, allowing for precise maintenance scheduling that ensures safe and efficient operations, thereby reducing the risk of catastrophic failures [1].The integrated plant performance management of the cement factories aims to improve output product quality and efficiency by using the technique of Condition Based Maintenance (CBM). Vibration condition monitoring is an active technique employed to detect common issues such as imbalances, misaligned couplings, and bent shafts. details various vibration analysis techniques, including advanced signal processing methods that improve fault detection rates in rotating machinery [2][3].Vibration in rotating equipment can compromise structure safety, negatively impact machinery, and make operators lives challenging. Resonance is a physical phenomenon in which an external force or a vibrating system forces another system to oscillate with greater amplitude at a specific frequency called the natural frequency. Resonance can cause an increase in amplitude that occurs when an object vibrating at its natural frequency absorbs energy from a nearby object vibrating at the same frequency. Therefore, when designing machines, engineers must consider not only the natural frequency of the machine but also the maximum vibration amplitudes during resonance frequencies to avoid damage to the machine and ensure its proper functioning [4]. Every mechanical system has its natural frequencies, which are the frequencies at which the system naturally tends to vibrate. These frequencies depend on the system's geometry, material properties [5], and boundary conditions. When the excitation frequency (in this case, the compressor speed) matches one of the natural frequencies, resonance occurs [6][7][8]. To avoid exciting a particular resonance, a structure's inherent frequency and vibrational mode shape should be carefully considered [9].

Maintenance reports from the Souq Al-Khamis Cement Factory indicate high vibration levels in the VML 60 screw-type cement mill compressors, leading to frequent stoppages. Notably, the compressors themselves show no clear mechanical or design flaws. The compressors were newly installed without base frames, instead mounted on workshop-fabricated bases without engineering analysis. The excessive vibration suggests improper foundation design is causing resonance issues and compressor shutdowns. In this case, one can suggest that the natural frequency of the compressor base frame may be matching the operating frequency of the compressor, resulting in resonant vibration. Proper engineering analysis during base frame design could have potentially identified and avoided this resonance condition. Rectifying the foundation design deficiencies is imperative to resolve the compressor vibration problems.

At the Suq Al-Khamis Cement Factory, the investigation commences with an examination of the natural frequencies and mode shapes associated with the compressor base frame, utilizing the Finite Element Method (FEM) through the ANSYS software platform. Subsequently, practical measurements will be performed employing the PHYPHOX App Vibration Analyzer to gather vibrational data and rotating speed frequency from multiple locations on the compressor.

This study's focus on diagnosing high vibration causes in screw air compressors is crucial in the cement manufacturing industry. By identifying and addressing resonance issues, the findings aim to prevent unexpected equipment failures that can lead to hazardous situations for operators and damage to machinery. The analysis confirmed that resonance was occurring due to the convergence of the compressor excitation frequencies and the natural frequencies of the insufficiently designed bases. When the external forcing frequency of the operating compressor matched the inherent natural frequency of the base frame, excessive resonant vibrations were produced.

2. Methodology

Vibration issues with the vital VML 60 screw compressors at Souq Al-Khamis Cement Factory were investigated by analyzing natural frequencies and avoiding resonance conditions. To start, finite element modeling (FEM) using ANSYS software simulated the natural frequencies and vibration modes of the compressor base frames. Next, vibration measurements using the PHYPHOX app identified the speed fundamental and its harmonic frequencies induced by the rotating compressors. Charles Riley stated that the PHYPHOX app offers a robust and configurable collection of sensor-based experiments that can be run using just a smartphone. This app provides a platform for working with emerging techniques for measuring vibrations without direct contact [10]. By comparing the simulated natural frequencies of the bases with the measured operating excitation frequencies, problematic resonance conditions could be identified. When specific natural frequencies of the insufficient base frames aligned with compressor forcing frequencies, resonance occurred, causing excessive vibrations. This approach allowed targeted design improvements to shift the natural frequencies away from resonant conditions.

2.1. Simulation Studies

2.1.1. Geometric Modeling

After measuring the actual dimensions of the base frame of compressor at the factory. A 3D model of the steel Q235 compressor base frame was simulated in SolidWorks with dimensions of 2400 mm length, 800 mm width, and 200 mm height, as shown in Figure 1. This 3D model was then imported into ANSYS for additional analysis using the finite element method.

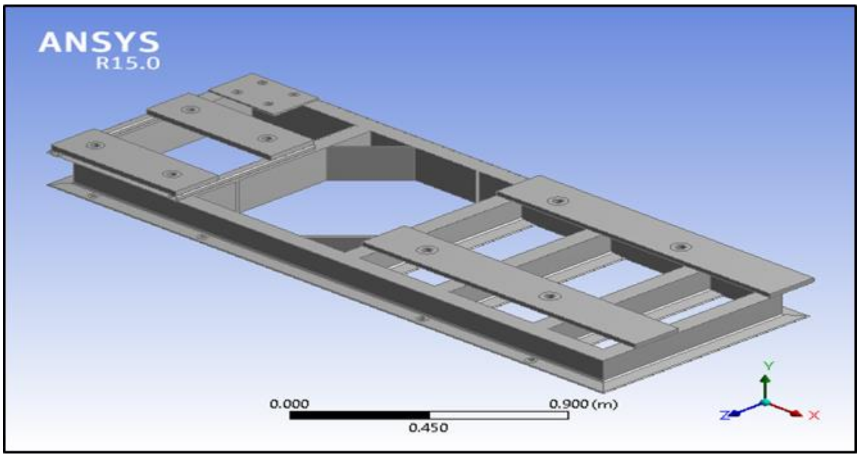

Figure 1: Compressor base frame geometric details.

The total mass of the compressor system, with all components, was estimated at 1481 kg. To simulate real-world mounting conditions, the model incorporated 8 bolts securing the base frame foundation, with zero degrees of freedom at each of the bolt holes. All meshing operations were carried out by using ANSYS Workbench, a commercial finite element package[11].

2.1.2. Meshing refinement study

ANSYS Workbench provided several parameters to evaluate the quality of the generated mesh, including orthogonal quality, aspect ratio, skewness, and element quality. Skewness was a key factor examined in this analysis. An ideal mesh element has zero skewness, while elements with non-zero skewness are considered low quality. In general, elements with skewness above 1 are considered unviable. A well-meshed domain should have negligible elements with skewness of 1. Acceptable mesh quality requires average skewness below 0.4 [12][13] [14]. In this study as shown in Figure 2 below, most elements in the analysis had skewness under 0.35 of base frame geometry which is the least recommended result, according to the above references. Therefore, the mesh metrics indicated that adequate mesh quality was achieved overall, with very few highly skewed elements that could affect solution accuracy.

The aspect ratio, which measures the degree of stretching of 3D elements, was another metric used to evaluate mesh quality. It is defined as the ratio between the maximum and minimum distances from the element center to either the face centers or the nodes [15]. For a good quality mesh, the average aspect ratio should be less than 5. As shown in Figure 3, most elements had aspect ratios below 3.5. With a majority tetrahedral mesh, the low aspect ratios combined with reasonable skewness values indicated that the generated mesh was of acceptable quality in terms of both parameters. Keeping aspect ratios and skewness low produced a high-quality mesh suitable for accurate finite element analysis [16][17][18].

LICASE
المؤتمر الليبي الدولي للعلوم التطبيقية و الهندسية
عدد خاص بالمؤتمرالليبي الدولي للعلوم
التطبيقية والهندسية دورته الثانية (II)
2024 / 10 / 30-29
https://orcid.org/0009-0009-5409-692
المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ
تم استلام الورقة بتاريخ:8/ /2024م وتم نشرها على الموقع بتاريخ: 30/ 2024/10م

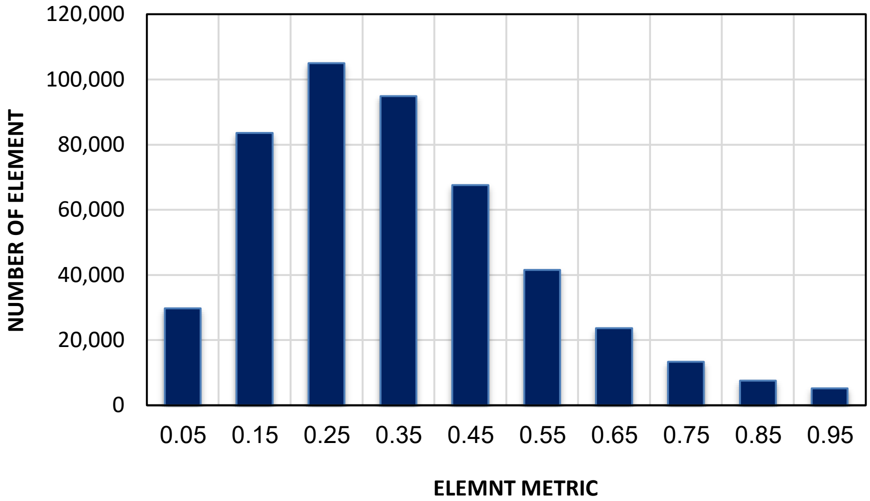

Figure 2: Skewness of the elements.

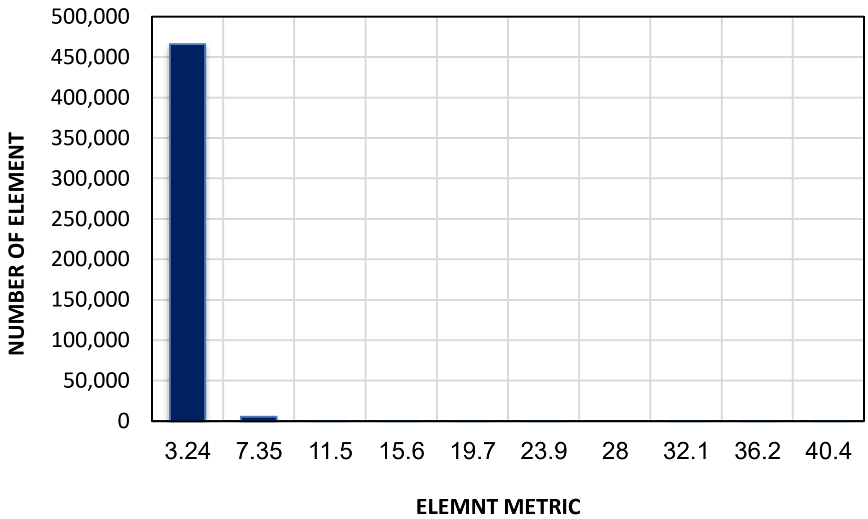

Figure 3: Aspect ratio of the elements.

The geometric refinement study aims to get excellent numerical solutions for the governing equations at each mesh node by minimizing the uncertainty resulting from the discretization. Static structural analysis findings from various mesh types are compared to achieve this, and the stability of the result is verified when the element size is adjusted [19]. Figure 4 shows how increasing the number of mesh elements affected solution convergence for the natural frequency mode shapes of interest. Initially with 10,000 elements, the solution fluctuated rapidly. As the mesh density increased to 100,000 elements, the result approached a stable value. At 450,000 elements, the solution appeared well-converged, with minimal change in natural frequencies. This indicated that 450,000 elements provided an adequately refined mesh for accurate solutions. Thus, this density was selected for further analyses. Figure 5 displays the final compressor base frame mesh consisting of 450,000 elements of type TET10 elements (10-node tetrahedral) to providing sufficient resolution for stable natural frequency predictions.

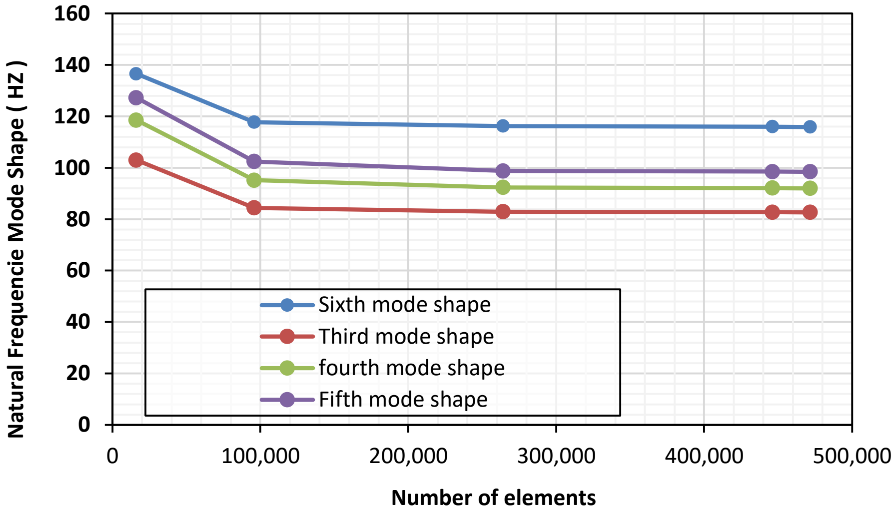

Figure 4: Mesh elements stability depending on number of mesh elements

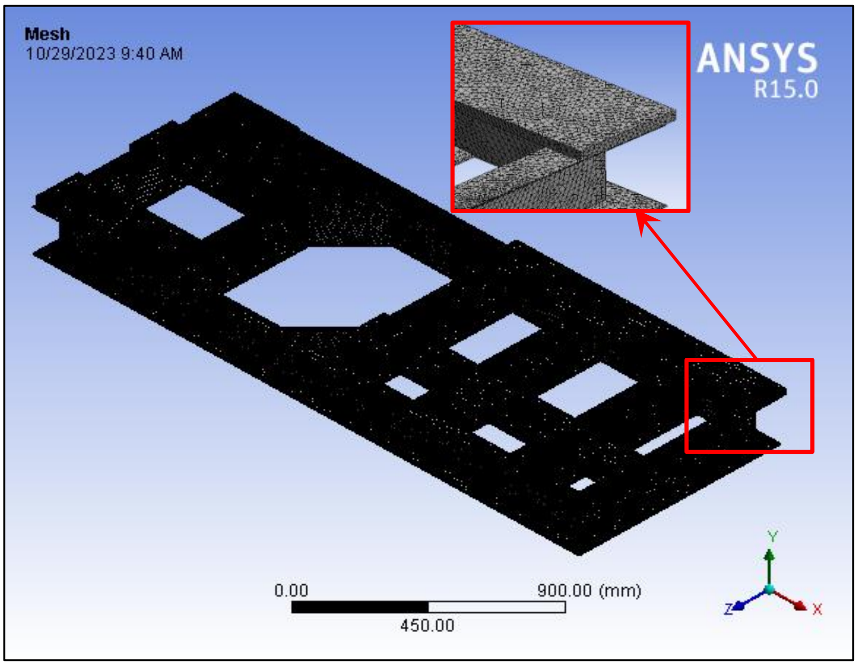

Figure 5: Final meshing of the base frame.

2.1.3. Boundary Conditions

Appropriate boundary conditions are crucial in finite element analysis to ensure the model accurately represents the real physical system. Boundary conditions constrain the solution space and provide reference points for the loads and restraints acting on the structure. They must replicate the actual constraints of the boundaries, connections, and supports. In the actual simulation, the ANSYS model is being fixed by 8 support bolts which are applied at the bottom of the compressor base frame. Gravity loads were applied at remote points coinciding with the center of mass of the motor, compressor, and air filter components. Their respective weights of 740 kg, 686 kg, and 55 kg were incorporated in the loads. Additionally, the dynamic operating loads were applied in the form of inertial forces acting on the components. Figure 6 illustrates the locations of the fixed bolts, gravity loads, and inertial forces representing the real-world constraints on the frame during compressor operation.

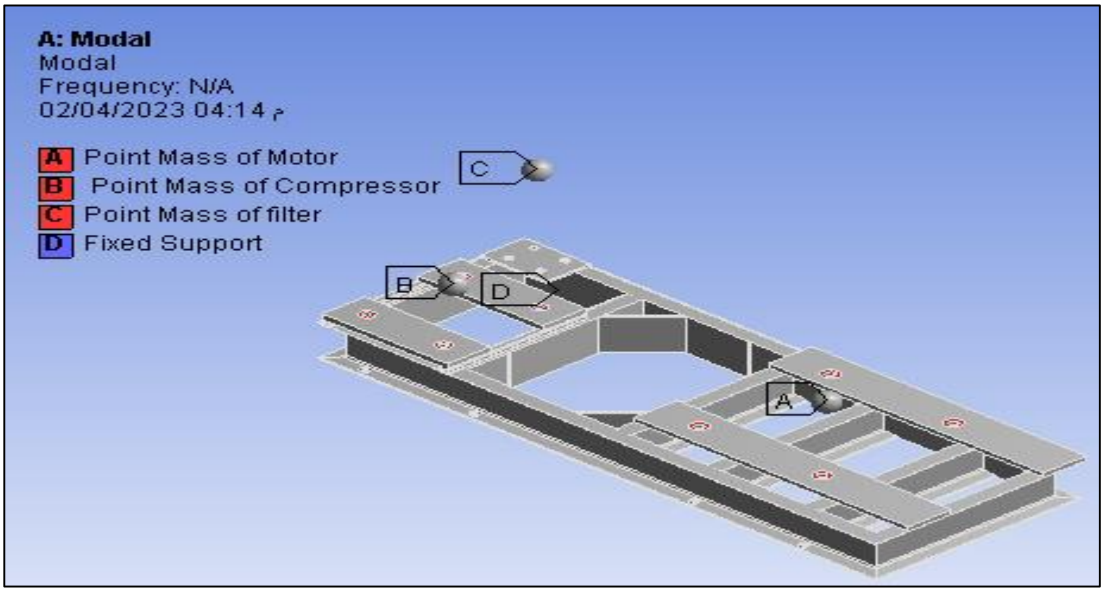

Figure 6: Boundary conditions of the base frame.

2.2. Rotating Frequency Measurement

The screw compressor operates at 7393 rpm (123.217 Hz), driven by a 200 kW three-phase induction motor rotating at 2975 rpm (49.6 Hz). The compressor has two lobes on the main (male) rotor and one more on the gate (female) rotor. To obtain axial, radial and vertical vibration results, the PHYPHOX App was used to characterize the system vibration and resonance, up to 200 Hz. The PHYPHOX App is a versatile tool for measuring various physical quantities using smartphone sensors, primarily aimed at educational purposes[20]–[22]. Its accuracy can vary depending on the specific type of measurement conducted, such as acceleration, sound, or light. Generally, while the app provides reliable data for basic experiments, users are advised to calibrate their devices with known standards to enhance measurement precision [23].

Table 1.Table 1.Accelerometer available of phyphox Sensor Database[23]

Name	lsm6ds3c Accelerometer Non-wakeup
Vendor	STMicro
Range	78m/s²
Resolution	0.0024m/s²
Rate	414.1Hz
Average	9.248m/s²
Standard deviation	0.013 m/s²

The app interfaces with the phone's accelerometer, gyroscope, microphone, and camera to provide various measurement capabilities. PHYPHOX includes tools for frequency analysis, order tracking, rotor balancing, and machine diagnostics. Its automated reporting documents overall vibration levels, frequency contents, and trends. While limited by sensor sampling rates, PHYPHOX provides economical vibration measurements for basic machine condition

عدد خاص بالمؤتمرالليبي الدولي للعلوم
التطبيقية والهندسية دورته الثانية (II)
2024 / 10 / 30-29
https://orcid.org/0009-0009-5409-692
تم استلام الورقة بتاريخ:8/ /2024م وتم نشرها على الموقع بتاريخ: 30/ 10/2024م

monitoring and troubleshooting. Its portability and ease of use make the app accessible for a range of shop floor or field vibration analysis needs. Measurements were taken with the phone attached near the installed compressor, shown in Figure 7. Further analysis would be needed to fully capture the vibration behavior at the higher operating speed, but the app measurements served as a preliminary investigation of the resonance issues.

Figure 7: Vibration measurements with a Phyphox App Vibration analyzer.

3. Results and Discussions

3.1. Numerical Analysis

The first six natural frequencies of the compressor base frame and their associated mode shapes were calculated as displayed in Figure 8. The first mode at 24.502 Hz (Figure 8a) involved vertical oscillation at the filter end of the base. The second and third modes at 66.75 Hz and 82.68 Hz (Figures 8b-c) exhibited vertical vibration in the compressor region. The fourth and fifth modes at 91.99 Hz and 98.43 Hz (Figures 8d-e) showed horizontal oscillation near the compressor mount. The sixth mode at 115.9 Hz (Figure 8f) displayed intense vertical vibration at a motor mounting point, with displacement decreasing along the x-axis away from the excited mount. This mode's proximity to the 123.217 Hz compressor speed makes it most critical. In summary, the analyses predicted increasing vibration and resonance behavior starting from the sixth mode shape. To mitigate the resonance, the sixth mode's natural frequency requires adjustment away from the forcing frequency. The sixth mode shapes and frequency dictate the frame's dynamic amplification, indicating design changes should target this mode.

LICASE
المؤتمر الليبي الدولي للعلوم التطبيقية و الهندسية
عدد خاص بالمؤتمرالليبي الدولي للعلوم
التطبيقية والهندسية دورته الثانية (II)
2024 / 10 / 30-29
https://orcid.org/0009-0009-5409-692
المجلة الدّولية للعلوم والتقنية
International Science and Technology Journal
ISTJ
وتم نشرها على الموقع بتاريخ: 30/ 2024/10م
تم استلام الورقة بتاريخ:8/ /2024م

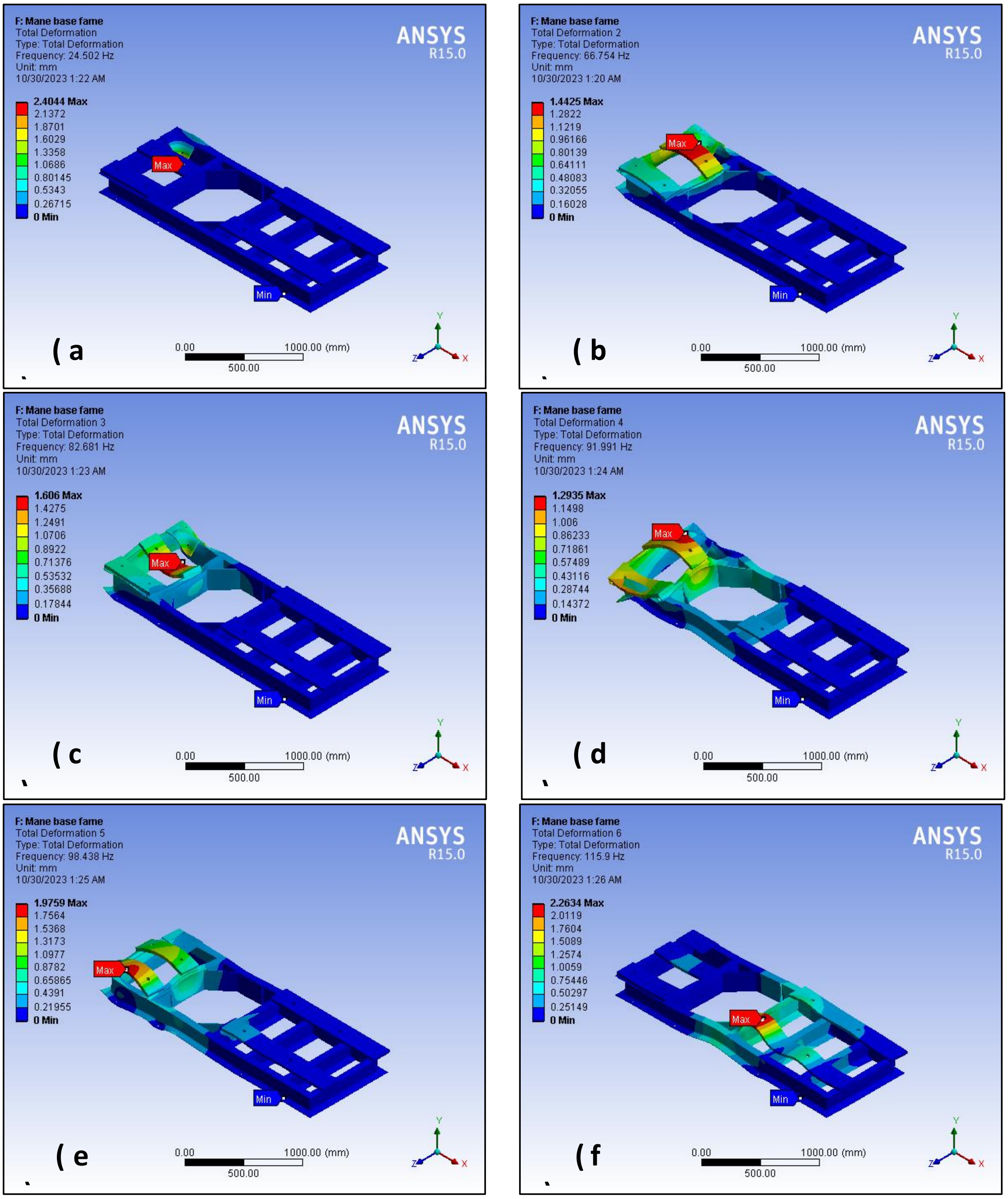

Figure 8: First six vibration modes of the original compressor base frame. (a) First mode at 24.5Hz; (b) Second mode at 66.8Hz; (d) Third mode at 82.68Hz; (d) Fourth mode at 91.99Hz; (e) Fifth mode at 98.435Hz; (f) Sixth mode at 115.9Hz.

3.2. Practical Analysis

The PHYPHOX App measured vibration signals in three directions on the motor, compressor, and base frame as shown in Figure 9a. The sensor exhibited high sensitivity, detecting a dominant frequency of 49.9 Hz at the motor which aligns with the 2975 rpm motor speed. This fundamental motor frequency had high amplitude compared to harmonics.

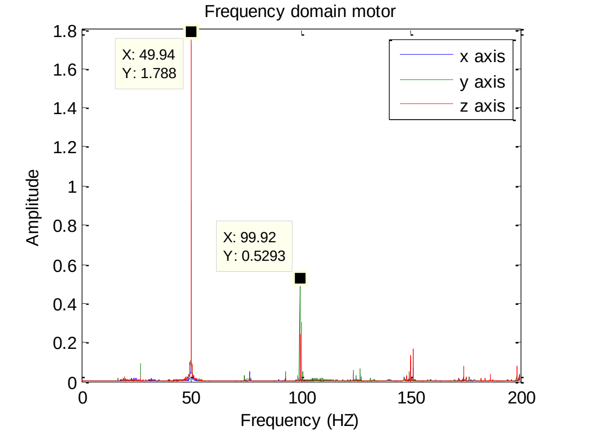

Figure 9-a: Spectrum of vibration signal at position I

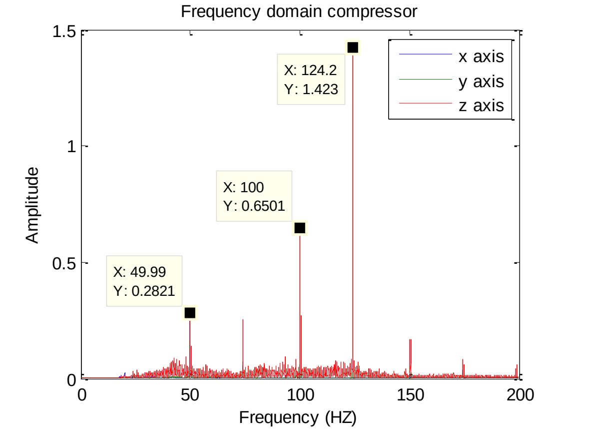

Figure 9-b: Spectrum of vibration signal at position II

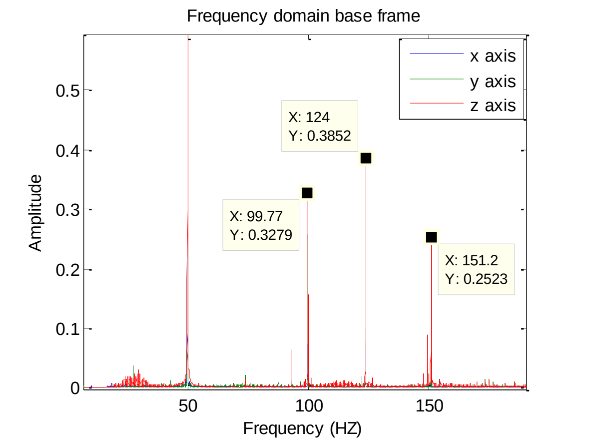

Figure 9-c: Spectrum of vibration signal at position III

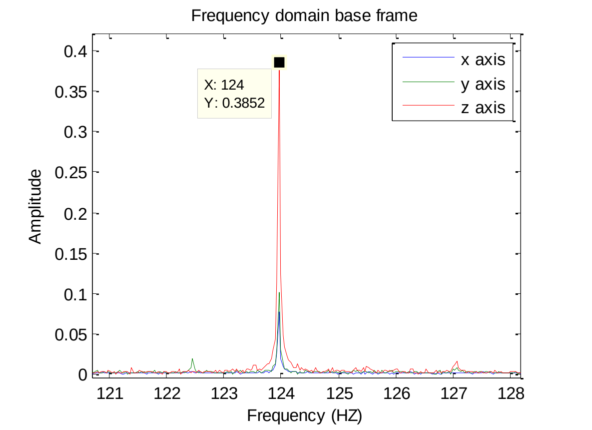

Figure 9-d: Spectrum of vibration signal at position III

At the compressor, Figure 9b shows a large 124 Hz vibration corresponding to the compressor speed. This frequency was also observed in the base frame (Figures 9c-d), indicating vibration transmission from the compressor to the foundation. With low amplitudes at other frequencies, the 124 Hz compressor forcing vibration could potentially excite resonance if matching one of the frame's natural frequencies. In summary, the PHYPHOX measurements identified the primary forcing frequency of the compressor at 124 Hz. The presence of this excitation frequency in the base frame suggests potential resonance coupling is causing the high vibrations.

3.3. Discussion

Figure 10 compares the first 10 natural frequencies of the ANSYS base frame model to the forcing frequencies from the compressor operating speed and harmonics. The dashed circle highlights the matching between the 115.9 Hz sixth mode natural frequency and the 123.217 Hz compressor speed excitation frequency. This matching of the structure's resonant frequency and the input vibration source indicates a high likelihood of resonance causing the observed vibrations. Considering the resonance condition has been diagnosed, mitigation solutions can be developed by shifting the frame's sixth mode dynamic response away from the operating frequency.

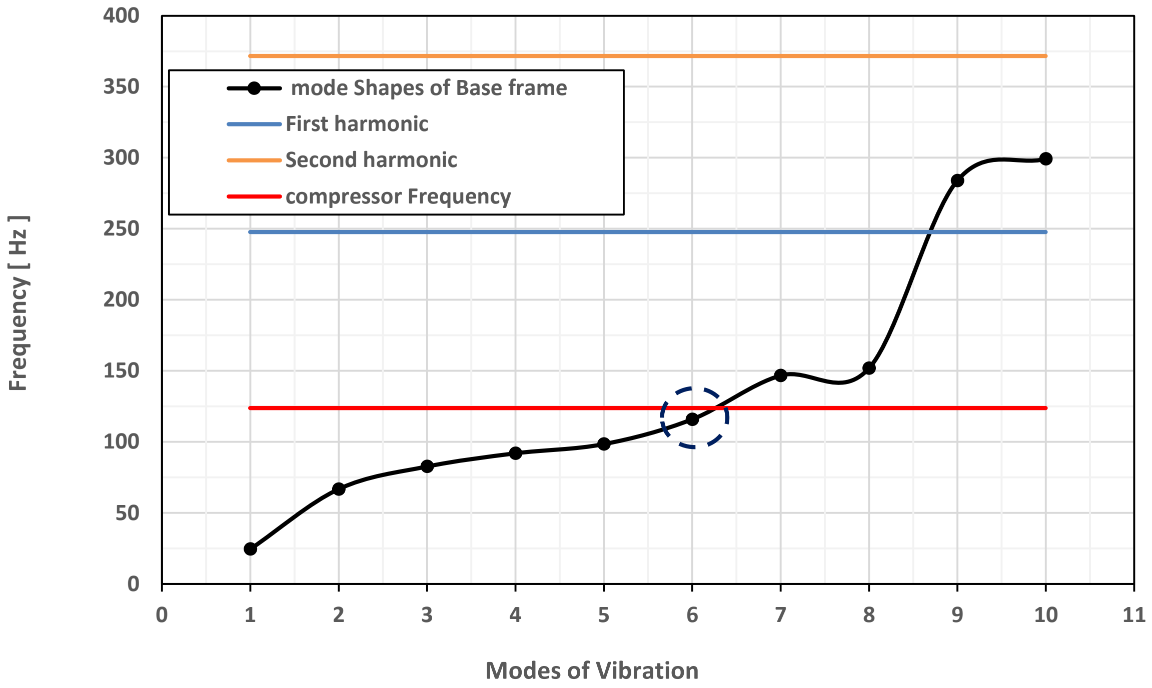

Figure 10: Compressor base frame structure and related modal frequency.

4. Conclusion

This study investigated resonance issues causing excessive vibration in the VML 60 screw compressor at Souq Al-Khamis Cement Factory. The compressor base frame's natural frequencies and mode shapes were analyzed numerically using finite element modeling (FEM). Vibration measurements from the PHYPHOX App characterized the frequency content of the compressor excitation forces. A comparison of the natural and forcing frequencies revealed a resonance condition arising from the alignment of the 115.9 Hz sixth mode with the 123.217 Hz compressor operating speed. This resonance produced severe vibrations and frequent cement mill shutdowns. Despite no inherent mechanical defects, the compressor was installed improperly on an improvised base lacking engineering analysis. In summary, the modal analysis techniques identified resonance as the root cause of vibration by elucidating the structure's dynamic properties. Deriving the natural frequencies, damping ratios, and mode shapes provided critical insights into the frame's vibration mechanisms. This understanding of the resonance condition will facilitate targeted redesigns to avoid operating at resonant frequencies.

Reference

[1] E. N. Johnson, I. W. Hilary, O. E. E, and I. R. Obinna, "Design Based Condition Maintenance in Oil and Gas Sector, Compendium of the Techniques and Procedure," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 10, no. 3, pp. 2157–2164, Mar. 2022, [Online]. Available: https://www.ijraset.com/best-journal/design-based-condition-maintenance-in-oil-and-gas-sector

[2] R. Ferrari, M. Zola, A. Cornaggia, and E. Rizzi, "Advanced signal processing methodology of vibration response data toward Structural Health Monitoring purposes," *J. Phys. Conf. Ser.*, vol. 2647, no. 18, p. 182040, Jun. 2024, doi: 10.1088/1742-6596/2647/18/182040.

[3] A. Moshrefi and F. Nabki, "Advanced Industrial Fault Detection: A Comparative Analysis of Ultrasonic Signal Processing and Ensemble Machine Learning Techniques," *Appl. Sci.*, vol. 14, no. 15, p. 6397, Jul. 2024, doi: 10.3390/app14156397.

[4] R. Markert and M. Seidler, "Analytically based estimation of the maximum amplitude during passage through resonance," *Int. J. Solids Struct.*, vol. 38, no. 10–13, pp. 1975–1992, 2001, doi: 10.1016/S0020-7683(00)00147-5.

[5] M. Neubauer, F. Schwaericke, V. Radmann, E. Sarradj, N. Modler, and M. Dannemann, "Material Selection Process for Acoustic and Vibration Applications Using the Example of a Plate Resonator," *Materials (Basel).*, vol. 15, no. 8, p. 2935, Apr. 2022, doi: 10.3390/ma15082935.

[6] S. S. Rao and P. Griffin, "Mechanical Vibrations Fifth Edition in SI Units," *Mech. Vib.*, p. 62, 2011.

[7] A. Majid, E. Abdeddine, K. Zarbane, and Z. Beidouri, "Experimental and Analytical Approach to Study the Effect of Large Vibration Amplitude of Rectangular Plates," *J. Vib. Eng. Technol.*, vol. 10, no. 8, pp. 3011–3023, 2022, doi: 10.1007/s42417-022-00533-9.

[8] Y. Liu and F. Chu, "Nonlinear vibrations of rotating thin circular cylindrical shell," *Nonlinear Dyn.*, vol. 67, no. 2, pp. 1467–1479, 2012, doi: 10.1007/s11071-011-0082-7.

[9] G. Gertie, "historic STRUCTURES Tacoma Narrows Bridge Failure 1940," pp. 60–63, 2022.

[10] C. Riley, "Mobile Phone-Based Contact and Non-Contact Vibration Sensing for Structural Dynamics Teaching Laboratories," *ASEE Annu. Conf. Expo. Conf. Proc.*, no. September, 2023, doi: 10.18260/1-2--43662.

[11] C. N. Hsu, "Experimental and performance analyses of a turbomolecular pump rotor system," *Vacuum*, vol. 121, pp. 260–273, 2015, doi: 10.1016/j.vacuum.2015.06.029.

[12] "How to Verify Mesh Quality in ANSYS Workbench - FEA Tips." Accessed: Nov. 07, 2023. [Online]. Available: https://featips.com/2021/05/07/how-to-verify-

mesh-quality-in-ansys-workbench/
[13] Ansys Inc., "Mesh Quality And Advenced Topics Ansys Workbench 16.0," *Ansys*, pp. 1–37, 2015.
[14] B. Fabritius and G. Tabor, "Improving the quality of finite volume meshes through genetic optimisation," *Eng. Comput.*, vol. 32, no. 3, pp. 425–440, 2016, doi: 10.1007/s00366-015-0423-0.
[15] M. H. H. Ishak *et al.*, "Effects of aspect ratio in moulded packaging considering fluid/structure interaction: A CFD modelling approach," *J. Appl. Fluid Mech.*, vol. 10, no. 6, pp. 1799–1811, 2017, doi: 10.29252/jafm.73.245.27083.
[16] G. A. Muñoz, "MESH QUALITY AND ADVENCED TOPICS ANSYS WORKBENCH 16.0." Accessed: Nov. 07, 2023. [Online]. Available: https://www.academia.edu/16970000/MESH_QUALITY_AND_ADVENCED_TOPICS_ANSYS_WORKBENCH_16_0
[17] A. Javidinejad, "FEA Practical Illustration of Mesh-Quality-Results Differences between Structured Mesh and Unstructured Mesh," *ISRN Mech. Eng.*, vol. 2012, pp. 1–7, 2012, doi: 10.5402/2012/168941.
[18] J. P. Dittmer, C. G. Jensen, M. Gottschalk, and T. Almy, "Mesh Optimization Using a Genetic Algorithm to Control Mesh Creation Parameters," *Comput. Aided. Des. Appl.*, vol. 3, no. 6, pp. 731–740, 2006, doi: 10.1080/16864360.2006.10738426.
[19] DEIST FH and DIMITRIOU C, "Finite Element Method," *S Afr Mech Eng*, vol. 19, no. 5, pp. 124–126, 1969, doi: 10.3156/jfuzzy.6.2_246.
[20] L. R. Putri, K. V. Febrianti, A. A. Adji, and F. Arsi, "Undergraduate Engineering Students' Attitude Towards the Use of Phyphox in Physics Experiment," *IJIET (International J. Indones. Educ. Teaching)*, vol. 7, no. 2, pp. 319–332, 2023, doi: 10.24071/ijiet.v7i2.6182.
[21] N. Imtinan and H. Kuswanto, "The Use of Phyphox Application in Physics Experiments: A Literature Review," *JIPF (Jurnal Ilmu Pendidik. Fis.*, vol. 8, no. 2, pp. 183–191, 2023, doi: 10.26737/jipf.v8i2.4167.
[22] I. Boimau and L. E. Laos, "Simple harmonic motion studied on spring-mass system using Phyphox application," *J. Ris. dan Kaji. Pendidik. Fis.*, vol. 11, no. 1, pp. 21–31, Apr. 2024, doi: 10.12928/jrkpf.v11i1.677.
[23] "phyphox – Physical Phone Experiments." Accessed: Aug. 15, 2024. [Online]. Available: https://phyphox.org/