Dynamic analysis of the reciprocating compressor package on the offshore platform

Y Zhao, W Wang, Q Zhou, J Feng, X Jia and X Peng
Xi'an Jiaotong University, Xi'an, Shannxi, China
E-mail: xypeng@mail.xjtu.edu.cn

Abstract. Reciprocating compressor packages are key equipment for the offshore platforms which are used for the pressurization and transportation of natural gas. Dynamic analyses of high-speed and flexible supported offshore compressor packages are more complex than that of compressors on land. The dynamic analysis techniques of the offshore reciprocating compressor package were studied including numerical modelling, excitation forces calculation, support boundary determination of the compressor package and load transmission between the compressor package and the offshore platform. The finite element model of the compressor package with multiple types of elements such as the pipe, beam and shell elements were established. Excitation forces mainly including gas forces inside cylinders, crosshead forces, acoustic shaking forces and unbalanced inertia forces were calculated. In order to investigate the influence of the flexibility of the platform on dynamic characteristics of the compressor package and set reasonable boundaries for the support structure, three kinds of support boundaries were compared. The support points of columns and vertical beams on the layer of deck where the compressor package is installed were determined to be the most suitable ones. Super-element method was applied to implement the load transmission from the compressor package to the platform. The analysis techniques herein were successfully applied to the dynamic analysis of an offshore reciprocating compressor package in an engineering project.

1. Introduction
Reciprocating compressor packages are key equipment for offshore platforms. Dynamic loads such as unbalanced inertial forces and gas forces inside cylinders can induce vibrations on the compressor and the offshore platform as well [1]. Severe vibration will reduce the reliability of the offshore platform [2]. Dynamic analyses of high-speed and flexible supported offshore compressor packages are more complex than that of compressor packages on land. Therefore, it is of great importance to study the vibration characteristics of offshore compressor packages.

Dynamic analysis of the compressor package has drawn much attention in recent years. Eberle et al. [3] conducted numerical analysis for a reciprocating compressor, and found that the deflection of the compressor frame due to gas forces may have significant effects on dynamic responses of the compressor package. Giacomelli et al. [4] developed a finite element model of a reciprocating compressor’s cylinder manifold, and calculated the vibration velocity responses under the acting of acoustic shaking forces and cylinder gas loads. Passeri et al. [5] generated a super-element of the compressor frame based on the sub-structuring technique to achieve the balance between calculation accuracy and computation time. However, little attention has been focused on the high-speed and flexible supported reciprocating compressors packages on the offshore platform.
In this paper, the dynamic characteristics of the offshore reciprocating compressor package were studied from four aspects. Firstly, the numerical models of the compressor package and offshore platform were established and coupled. Secondly, excitation forces in the compressor package were calculated. Thirdly, three kinds of support boundaries were compared to determine reasonable support boundary for the compressor package. Finally, the super-element method was applied to implement the load transmission from the compressor package to the platform.

2. Numerical modelling

Appropriate element types were chosen for different components of the structure to improve calculation efficiency. Numerical models of the compressor package and offshore platform with multiple element types were established and coupled.

2.1. Numerical model of the compressor package

The geometric model of the compressor package as shown in figure 1(a) was simplified before numerical modelling due to its complexity. Instrumentations, oil tubes, cooling water pipes and non-load-bearing components such as the fence and handrails were removed. The simplified geometry model mainly consists of the skid, pedestal, compressor, motor, scrubbers, buffer tanks, coolers and main pipelines. The numerical model of the compressor package with multiple element types were established, as shown in figure 1(b). The skid, pedestal, scrubbers, buffer tanks and coolers were simplified as shell elements. Included pipes were modelled with pipe elements as appropriate. The compressor, motor and pipe supports were modelled with beam elements. Masses of the removed components were considered by distributing mass elements over the skid area. Based on the assumption that all welds are 100% strength, different components were connected with rigid elements. A total of 46281 elements and 40742 nodes were generated in this model.

![Geometrical model](a) Geometrical model. ![Numerical model](b) Numerical model.

**Figure 1.** The compressor package.

2.2. Numerical model of the offshore platform

The jacket offshore platform consists of the upper structures and foundation structures (jackets). The foundation structures were ignored to reduce computational complexity. The upper structures were modelled and the bottom of the eight columns were fixed constrained, as shown in figure 2. The beams and decks were modelled as beam and shell elements, respectively. Equipment on the offshore platform except the compressor package was simplified as mass elements. A total of 32540 elements and 14482 nodes were generated in this model.
2.3. The coupled model
The numerical model of the compressor package and offshore platform were coupled by creating rigid regions between the skid of the compressor package and the beams of the platform, as shown in figure 3. A total of 78821 elements and 55224 nodes were included in the coupled model.

3. Excitation forces calculation
The vibration excitation forces of reciprocating compressor package mainly include unbalance inertia forces and moments, gas forces, crosshead forces and acoustic shaking forces. All of these forces consist of multiple harmonics which can be obtained by the Fourier decomposition. In this paper, the speed of the compressor is 994 rpm, thus the first order excitation frequency is 16.6 Hz and its multiples are also the excitation frequencies. The first order harmonic of excitation forces were used for subsequent dynamic response analyses.

3.1. Unbalanced inertia forces and moments
For each throw of cylinder, the reciprocating inertia force $F_{ls}$ on reciprocating components and rotating inertia force $F_r$ on rotating components are given by

\[ F_{ls} = m_l a = m_r r \omega^2 (\cos \theta + \lambda \cos 2\theta) \]  \hfill (1)

\[ F_r = m_r a_r = m_r r \omega^2 \]  \hfill (2)

where $m_l$ is the equivalent reciprocating mass, $m_r$ is the equivalent rotating mass, $\lambda$ is the ratio of the crank radius and connecting rod length, $\theta$ is the crank rotation angle and $\omega$ is the angular velocity. The balanced-opposed reciprocating compressor discussed here has four throws and two stages, and inertia
forces and moments of all throws didn’t completely balance. Unbalanced inertial forces and moments were supplied by the compressor manufacturer.

3.2. Gas forces and cross-head guide forces
The gas force inside cylinders will make the cylinder suffer cyclical tensile or compressive loads and induce vibration of the compressor. The gas force, reciprocating inertia force and reciprocating frictional force are all along the axis of the cylinder, and their resultant force is called the piston force \( F_p \). The piston force transmitted to the cross-head through the piston rod was divided into two forces—the connecting rod force and cross-head guide force. The direction of the crosshead guide force alternated as the crankshaft rotating, resulting in continuous percussion between the crosshead and the crosshead guide. The crosshead guide force \( F_N \) can be represented as

\[
F_N = F_p \tan \beta = \frac{F_p \lambda \sin \theta}{\sqrt{1 - \lambda^2 \sin^2 \theta}}
\]  

(3)

3.3. Acoustic shaking forces
The periodic suction and discharge of the reciprocating compressor will cause gas pulsation in the piping system, and induce acoustic shaking forces on the elbow, valve, reducer etc. The transfer matrix method was used to calculate acoustic natural frequencies and shaking forces in the piping system. The piping system was divided into some basic elements such as pipe, valve, tee and volume. Each element has a transfer matrix \( M \). The transfer matrix of the overall piping system is formulated by multiplying the transfer matrices of all the piping elements, as shown below.

\[
\begin{bmatrix} p_n \\ u_n \end{bmatrix} = M_{n,n-1} \cdot M_{n-1,n-2} \cdots M_{2,3} \cdot M_{1,2} \cdot \begin{bmatrix} p_1 \\ u_1 \end{bmatrix}
\]  

(4)

where \( p_i \) and \( u_i \) are the amplitude of perturbation pressure and velocity of the first node in the piping system, \( p_n \) and \( u_n \) are the amplitude of perturbation pressure and velocity of the last node in the piping system, respectively. The acoustic natural frequency, pressure unevenness and acoustic shaking forces can be obtained with relevant boundary conditions of the piping system.

4. Support boundary determination of the compressor package
Support boundary will affect dynamics of the structure. As for the compressor package on land, the foundation is generally ignored and the bottom of the skid is assumed as fixed constrained. However, the flexibility of support structures should be considered while investigating dynamics of the offshore compressor package. The whole coupled model of the offshore platform and compressor package as shown in figure 3 approaches reality well, but has the advantage of low computational efficiency. Ignoring the platform and applying fixed constraint directly on the compressor skid can significantly reduce calculation time, but will cause large errors. Therefore, determining a reasonable support boundary of the compressor package to shorten calculation time on the premise of ensuring the accuracy is of great importance in the vibration analysis of the offshore compressor package.

4.1. Three kinds of support boundaries of the compressor package
Three kinds of support boundaries were compared to check the effects of support structures to the dynamic characteristics of the offshore compressor package and determine a reasonable support boundary for the offshore compressor package. The harmonic response analysis was conducted and the displacement responses of the compressor package at 16.6 Hz were extracted. The results of the boundary A were considered as the baseline.

- Boundary A: The whole coupled model of the compressor and the offshore platform was used and the bottom of eight columns were fixed constrained, as shown in figure 3.
Boundary B: A part of the offshore platform was included to represent the flexibility of the support structure, and the support points of columns and vertical beams on the layer of deck were fixed constrained, as shown in figure 4.

Boundary C: The offshore platform was removed, and the welded points on the compressor skid were fixed constrained, as shown in figure 5.

4.2. Comparison of displacement responses
The displacement distributions of the compressor package with three support boundaries were shown in figure 6, figure 7 and figure 8, respectively. It can be seen that the maximum displacements of the compressor with boundary A, B and C were 1.437 mm, 1.246 mm and 0.103 mm, respectively. The displacements of all nodes on the compressor package were extracted and compared. The results of boundary A were considered as the baseline, the relative displacement error at each node of boundary B and C was calculated. The relative displacement errors were divided into six intervals: 0-10%, 10%-20%, 20%-30%, 30%-40%, 40%-50%, and >50%. The percentage of node number in each interval was shown in figure 9. It can be seen that the relative displacement errors at 67.9% nodes of the compressor package with boundary B were less than 20%, and the average relative error was 17.1%. The relative displacement errors at all nodes of the compressor package with boundary C were larger than 50%, and the average relative error was 93.2%. It was indicated that results of boundary B agreed well with the baseline, while results of boundary C had large discrepancy with the baseline.
Figure 8. Displacement of the compressor package with support boundary C.

Figure 9. Relative displacement errors of support boundary B and C.

Table 1 shows the comparison of calculation time and storage space of three support boundaries. It can be seen that compared with boundary A, boundary B can save 83.7% of calculation time and 67.8% of storage space, and boundary C can save 98.6% of calculation time and 89.7% of storage space.

Table 1. The comparison of calculation time and memory space of three support boundaries.

|                      | Boundary A (baseline) | Boundary B | Boundary C |
|----------------------|-----------------------|-----------|-----------|
| Calculation time (min)| 215                   | 35        | 3         |
| Storage space (GB)    | 8.70                  | 2.8       | 0.9       |

From above analyses, we can see that the support structure had great impact on the dynamics of the offshore compressor package and shouldn’t be ignored while conducting dynamic analysis of the offshore compressor package. Containing parts of the platform structure and applying fixed constraints on the support points of columns and vertical beams on the layer of deck can greatly improve computational efficiency on the premise of good accuracy, thus was recommended as the support boundary of the offshore compressor package.

5. Load transmission between the compressor package and the offshore platform
Since the excitation loads on the compressor package will affect the dynamics of the offshore platform, the load transmission method between the compressor package and the offshore platform is of great importance while investigating dynamics of the offshore platform. Using the whole coupled model of the offshore platform and compressor package is closest to reality, but will lead to the problem of large calculation time and storage space.

5.1. Three kinds of load transmission methods
Three kinds of load transmission methods between the compressor package and the platform were compared to check the effects of compressor package to the dynamic characteristics of the offshore platform and determine reasonable load transmission method.

- Method A: The whole coupled model of the offshore platform and compressor package as shown in figure 3 were used and set as the baseline. The excitation loads were exerted on the compressor package. The results of the boundary A were considered as the baseline.
- Method B: The coupled model of the offshore platform and mass elements which located on the installation of the compressor package was used to study the dynamic response of the
compressor package, as shown in figure 10. Since the compressor package wasn’t modelled in detail, the excitation loads couldn’t applied directly to the model. A harmonic response analysis was conducted to the compressor package model in which the fixed constrained were applied on the skid welding nodes and excitation loads were applied on the compressor and pipeline, and the reaction forces and moments at the skid welded nodes were extracted. The reaction forces and moments at the skid welded nodes obtained from the harmonic response analysis of the compressor package were applied to the coupled model of offshore platform and mass elements.

- **Method C:** The coupled model of the offshore platform and a super-element were used to obtain the vibration responses of the compressor package, as shown in figure 11. This simplified method is based on the substructure technique [6-7]. Firstly, the complete model of the compressor package was condensed to a super-element, the skid welding nodes and the loads applying nodes were selected as master nodes of the super-element, and a substructure analysis was conducted to generate the condensed mass and stiffness matrices of the super-element. Then, the model of the offshore platform were coupled with the super-element which only contained the DOFs of the master nodes, and the dynamic loads of the compressor package were applied to the master nodes of the super-element.

**Figure 10.** Load transmission method B between compressor package and offshore platform.

**Figure 11.** Load transmission method C between compressor package and offshore platform.

5.2. *Comparison of displacement responses*

The displacement distributions of the offshore platform at 16.6 Hz were shown in figure 12, figure 13 and figure 14, respectively. The maximum displacement the offshore platform with load transmission method A, B and C were 0.661 mm, 0.196 mm and 0.582 mm, respectively. The displacements on all nodes (14482 nodes) of the offshore platform at 16.6 Hz were extracted and compared. The results of load transmission method A were considered as the baseline, the relative displacement errors on each nodes of the offshore platform with load transmission method B and C were calculated. The relative displacement errors were divided into six intervals: 0-10%, 10%-20%, 20%-30%, 30%-40%, 40%-50%, and >50%. The percentage of node number in each interval was shown in figure 15. It can be seen that the relative displacement errors at 42.6% nodes of the offshore platform with load transmission method B were larger than 50%, and the average relative error of method B was 68.2%. The relative displacement error at 99.3% nodes of the offshore platform with load transmission method C were lower than 10%, and the average relative error of method C was 3.2%. It was indicated that the results of load transmission method C agreed well with the baseline, while results of method B had large discrepancy with the baseline.
Table 2 shows the comparison of calculation time and storage space of three kinds of load transmission methods. It can be seen that compared with load transmission method A, load transmission method B can save 42.3% of calculation time and 56.3% of storage space, and method C can save 31.6% of calculation time and 35.6% of storage space.

Table 2. The comparison of calculation time and memory space of three load transmission methods.

| Method          | Calculation time (min) | Storage space (GB) |
|-----------------|------------------------|--------------------|
| Method A (baseline) | 215                    | 8.70               |
| Method B          | 124                    | 3.8                |
| Method C          | 147                    | 5.6                |

From above analysis, we can see that the load transmission method C in which the compressor package was simplified as a super-element was more accurate than method B in which the compressor package was simplified as mass elements. It maybe because both of the mass and stiffness of the compressor package were taken into account in the super-element of method C, but the stiffness of the compressor package was not considered in method B. Besides, simplifying the compressor package as a super-element can greatly save the computational time compared to the whole coupled model of the offshore platform and compressor package. Therefore, it is advisable to simplify the compressor package to a super-element when performing vibration analysis for the offshore platform.
6. Conclusions
The most important conclusions of the present paper are as follows.

- Choosing appropriate element type for each component and establishing the numerical model with multiple types of element such as the beam, pipe, shell and mass elements is an efficient way to improve the efficiency of dynamic analysis of the compressor package and offshore platform.
- Unbalanced inertia forces and moments of the compressor were supplied by the compressor manufacturer. The gas forces inside cylinders and crosshead guide forces were calculated through dynamic calculation of the compressor. The acoustic shaking forces in the piping system were calculated by an acoustic analysis.
- The flexibility of the offshore platform will greatly affect the dynamics of the offshore compressor package. Containing parts of the platform structure near the compressor package and applying fixed constraints on the support points of columns and vertical beams on the layer of deck can greatly improve computational efficiency on the premise of good accuracy, thus was recommended as the support boundary of the offshore compressor package.
- The super-element method is an effective method to implement the load transmission from the compressor package to the platform while performing vibration analysis of the offshore platform.

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