Dynamic Analysis of Reciprocating Compressors on FPSO Topside Modules

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Abstract:

A growing number of reciprocating compressors are being used on Floating Production Storage and Offloading vessels (FPSO) for many applications. These compressors are significant sources of vibratory forces and can cause high vibrations of the compressors and FPSO module, resulting in costly and premature machine failures as well as safety concerns to operators in work areas. Owners and engineering companies often require a dynamic analysis of the production structure when high horsepower reciprocating compressors are employed to mitigate these issues.

Based on our experience with over 60 offshore reciprocating projects, this paper discusses new analysis techniques to calculate the amplitude and location of high vibrations on the module deck and to optimize the topside module design. An example is included that reviews an integrated design approach, combining the topside module structural model with the mechanical model of the compressor packages. A summary of the recommended specifications for performing dynamic analysis studies is included. This paper includes examples from recent projects, including a large FPSO project where three compressor packages were mounted on the topside module.

1 Introduction

Reciprocating compressors serve a number of purposes on offshore petroleum facilities, such as Floating Production Shipping and Offloading (FPSO) vessels. These compressors range from small vapour recovery compressors – typically 500 HP (370 kW) – to large, multi-stage compressors used in high pressure injection service that can be over 3000 HP (2240 kW). The reciprocating compressor, driver (engine or motor), piping, scrubbers, and pulsation bottles are packaged as a unit and loaded onto the FPSO. While this paper highlights FPSOs, the principles discussed apply equally to other floating and fixed offshore installations.

Reciprocating compressors generate high dynamic forces due to the motion of the mechanical components inside the compressor during delivery of gas to the system.

The dynamic forces, as shown in Figure 1, include:

- pressure pulsation induced forces
- mass unbalance
- crosshead forces
- gas force inside the compressor cylinder causing cylinder motion (cylinder stretch)
- misalignment

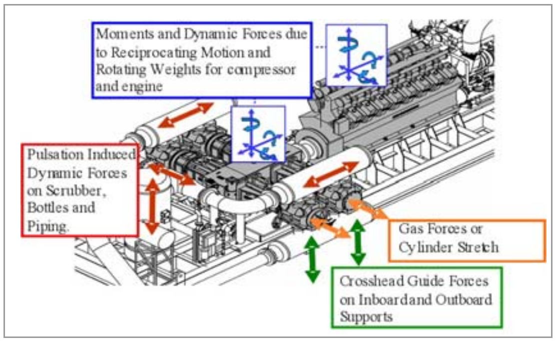

Figure 1: Dynamic Forces on Reciprocating Compressors

These forces can generate excessive vibrations on the piping, scrubbers, compressor frame, small bore attachments, compressor skid, and FPSO topside structure. Excessive vibration is the major cause of mechanical failures on reciprocating compressors.

Failures are costly and create safety concerns for operators. The offshore environment creates two other challenges for owners and operators:

- Repair and downtime costs have been estimated to be 4 to 5 times higher in offshore applications than most land based applications. This is due to the significant travel and logistic requirements. End users demand high reliability applications and can't afford vibration related problems.
- Space is at a premium on an FPSO or any offshore installation. The limited space requires a compact mechanical design for the piping, vessels, and heat exchangers. A compact design places more components close to the compressor. This means the layout is often complex and, therefore, compromises must be made between the support requirements, process requirements, access, and maintenance. As illustrated in Figure 2, this often results in a design that is more susceptible to vibration.

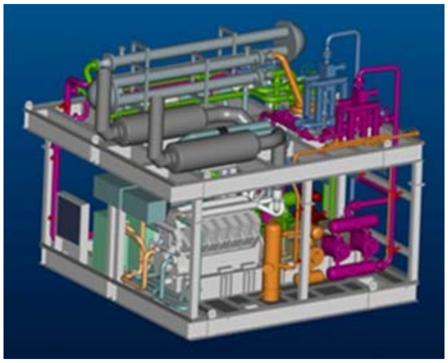

Figure 2: Compressor Module with Limited Space Results in Challenging Vibration Issues. (Courtesy of Universal Compression, Mustang, Chevron)

The purpose of this paper is to:

- Discuss what is included in a dynamic analysis and when it should be performed.
- Use actual case studies to illustrate methods that integrate the dynamic analysis with other project requirements to ensure the most cost effective solution.
- Describe challenges with vibration guidelines for offshore applications
- Give recommendations for specifying dynamic analysis studies

2 Dynamic Structural Analysis - Overview

Owners, engineering companies, and compressor packagers contract machinery consultants to perform studies on the reciprocating compressor package to mitigate vibration issues. A summary of the typical design studies is given in Figure 3. Some studies are recommended in API 618 4th edition (and the upcoming 5th edition) and are designated below by their “M” nomenclature. Others are specific to the package and its application.

Design Studies For Reciprocating Compressor Packages on FPSO and Offshore Platforms

- **Pulsation Analysis** (M2): assesses pulsations and unbalanced forces. Recommends solutions to control pulsation induced forces.
- **Compressor Performance Analysis** (M3): determines performance, pressure drop, and capacity, for the recommended pulsation control design.
- **Mechanical Analysis** (M4, M5, M6, M7, M8): calculates Mechanical Natural Frequency (MNF) of piping and cylinders, detunes mechanical design to avoid resonance, predicts vibration and stress in critical areas of piping, cylinders, and bottle internals. Gives recommendations to avoid vibration on the compressor package.
- **Piping Flexibility** (M11): determines piping system flexibility for cooler nozzle loads and piping stress due to thermal cycles, pipe weights, and bolt up strain effects (for coolers mounted off skid). *Note: API 5th edition will require the same consulting firm to complete both the Mechanical Analysis and Piping Flexibility studies.*
- **Torsional Vibration Analysis**: assesses crankshaft and coupling design, evaluates torsional stress for all operating conditions.
- **Skid Analysis**: consists of two components: (1) lifting and design review; (2) quasi-static analysis to assess loads due to transportation, ship motion, and wind during normal operation, storm condition, and blast conditions.
- **Dynamic Structural Analysis**: analysis of the topside structure or production deck structure with the reciprocating compressor package compressor structure to identify areas of high vibration due to dynamic loads from the reciprocating compressor.

Figure 3: Design Studies For Reciprocating Compressor Packages on FPSO and Offshore Platforms

A Dynamic Structural Analysis study (last study listed in Figure 3) is not unique to offshore applications and is sometimes conducted for land based systems. The scope of the analysis is somewhat different for land based systems as compared to an offshore unit, however the principles of the design process are similar.

Reciprocating compressors are mounted on a network of trusses and beams, called topside structures, deck structure, module, or “pancake” on FPSOs and platforms. These structures can be designed by the structural engineer to withstand the static and quasi-static loads using common practices. Designing the structure to withstand dynamic loads requires special consideration. The dynamic analysis must accurately determine if there are any structural resonances and calculate the expected vibrations. Resonance occurs when a Mechanical Natural Frequency (MNF) of the structure occurs at the same frequency as the dynamic forces described earlier.

The goal of this analysis is to evaluate the response of the skid and the topside structure to the equipment’s dynamic loads and provide recommendations to ensure vibrations are below guidelines.

The Dynamic Structural Analysis also includes:

- Evaluation of dynamic forces for all planned operating conditions. Note that focusing on the *perceived* worst case conditions is a short-cut that can miss actual worst case conditions. The changes in force amplitude and phase at different frequencies must be evaluated.
- Assessment of the interaction between multiple compressor units. The model should assess if the compressor units amplify the vibrations under specific conditions.
- Consideration of the FPSO deck dynamic stiffness at each module mounting location (stabbing point).
- Expanding the scope to include evaluations of the driver dynamic loads. The dynamic loads from a motor are typically low and can be ignored. The dynamic loads from any engine may be sufficient to cause vibration which, when added to the response from the compressor, could be over guideline.

3 Who Specifies a Dynamic Analysis? When is it Required?

Engineering consultants are typically responsible for design of the topside structure. The design often includes consideration of the static and quasi-static loads imposed on the structure by equipment mounted on the structure. The supply and design of this equipment is typically contracted to other parties by the engineering consultant doing the topside structure design.

The reciprocating compressor package is typically contracted to a provider of gas compression equipment that designs and constructs a unit to meet the required performance. The compressor packager is often held responsible for ensuring the dynamic response of the compressor package is acceptable. Holding the compressor packager up to this responsibility is, in many ways, unrealistic.

Typically, the reciprocating compressor package, such as seen in Figure 4, is designed to ensure that dynamic forces and the resulting response will be controlled to some reasonable level assuming that the package support (or foundation) will provide some restraint. It is possible to design a very robust reciprocating compressor package that requires minimal support from the topside structure, however the design of the compressor package may be very costly. The connections between the compressor package and the topside structure will still have some effect on the package response that could make the robust design ineffective. Alternatively, the compressor packager could design a relatively light-weight package that would require a stiff topside structure to control the dynamic response. The technically correct approach, and often most cost effective approach, for conducting the structural dynamic analysis is to conduct an overall or combined dynamic analysis of the compressor package dynamics and topside structure dynamics.

Figure 4: Example of Reciprocating Compressor on FPSO. Dynamic analysis of compressor forces on FPSO structure requires coordination between Machinery Consultant, Packager, and Engineering Consultant.

A third party Machinery Consultant is often contracted to conduct this overall dynamic analysis and make recommendations for the reciprocating compressor package design, topside structure design, and the connection between the two components. The dynamic analysis requires an intimate understanding of the reciprocating compressor dynamic loads that the topside structure Engineering Consultant and/or Compressor Packager generally do not have. Specialized modelling techniques are also required to accurately calculate the dynamic response.

The dynamic analysis of the reciprocating compressor package involves simulation of a lot of details in the compressor package design. The loads in the compressor must be calculated for a range of operating conditions. The forces acting on pulsation bottles and scrubbers from pressure pulsations must be calculated. The mechanical characteristics of the compressor frame, cylinders, pulsation bottles, scrubbers and other equipment must be included. All of these details will be, or may already have been, included in the mechanical study of the compressor package (API 618 studies). There are technical and commercial benefits to the owner, or end user, and engineering consultant from having one machinery engineering firm complete all dynamic analysis and pulsation studies on the reciprocating compressor package. It is beneficial to contract the dynamic analysis to a machinery engineering firm that specializes in dynamic analysis, which is typically the same firm that assesses the pulsation and dynamic analysis for compressor package (API 618) and skid design.

The decision to specify a dynamic analysis is ultimately based on a risk assessment of the application. The following attributes are useful for quantifying the risk:

- How critical is the application? What are the consequences (costs) associated with downtime and field modifications to the structural elements in an FPSO or platform?
- What is the size of the reciprocating compressor? Generally the larger the power requirement per compressor throw, the higher the dynamic forces will be:
  - 500 HP (370 kW) per throw is a high risk
  - < 200 HP (150 kW) per throw is a low risk
- How many reciprocating compressors are on each module?
  - 1 unit: low to moderate risk
  - >1 unit: high risk
- Is the reciprocating compressor fixed speed or variable speed? If the compressor operates at a single speed it is easier to detune structural MNFs away from resonance. Variable speed packages are a much higher concern for vibration due to risk of resonance.

4 Vibration Guidelines for Structural Dynamic Analysis

One basic criterion to assess the acceptability of the structural dynamics is vibration. Guidelines have been developed by many different organizations to ensure the health and safety of personnel as well as protect equipment from premature failure. Health and Safety Executive Offshore Technology Report 2001-068(1) gives general vibration guidelines for machinery and personnel. Other organizations such as ISO, DNV, ABS also have guidelines for vibration.

All reciprocating compressor manufacturers, motor manufacturers, and engine manufacturers have vibration guidelines, or vibration limits, to protect their equipment. Typical guidelines include a vibration amplitude specified at the crankshaft centerline in the horizontal, and sometimes vertical, direction. Some engine manufacturers include overall vibration guidelines in addition to frequency based guidelines. Note that vibration limits for shut-down of equipment that are specified by manufacturers should not be used as design guidelines.

Owners, operators, and engineering consultants may have their own vibration guidelines based upon their experience and specific requirements. Beta Machinery Analysis (Beta) has developed vibration guidelines for all aspects of evaluating reciprocating compressor installations. Figure 5 shows Beta's guidelines for piping, vessels, and compressor cylinders.

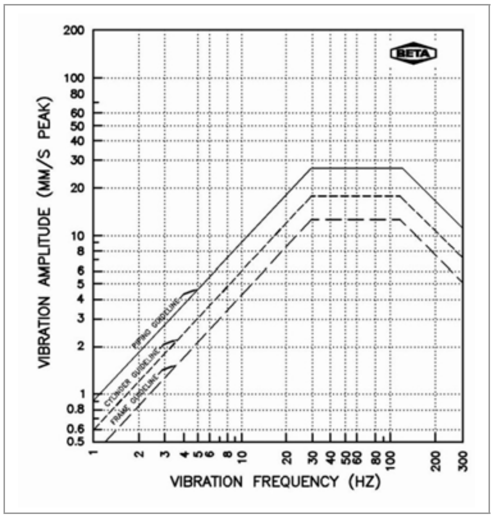

Figure 5: Vibration Guideline Chart for High Speed Reciprocating Compressors

A vibration guideline should be used as a guide to assess a design regardless of what vibration guideline is specified. The vibration guideline may be too stringent in some specific applications and it is acceptable to exceed the guidelines. In other cases, vibrations may be within guidelines but the resulting design is not able to tolerate the vibration. Vibrations should be used as a screening tool to assess the design; and closer inspection of the operating deflected shape should be done to determine if the vibrations are acceptable or not.

Consider the example shown in Figure 6. The figure shows a simplified cross-section of a compressor frame and skid. A typical vibration guideline for a high speed reciprocating compressor is 0.5 ips pk (13 mm/s pk) at the crankshaft centreline. A typical vibration guideline for skid vibration is 0.1 ips pk (2.5 mm/s pk). The vibrations shown in Cases 1 and 2 are within guidelines. Inspection of the direction of the vibration (or operating deflected shape) shows that the vibrations are in-phase for Case 1 and out-of-phase for Case 2. The vibrations for Case 2 are judged to be excessive and corrective actions are required.

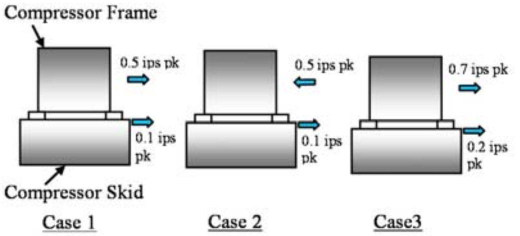

Figure 6: Schematic of Compressor Frame and Skid Operating Deflected Shapes

The vibration shown in Case 3 may, on first inspection, obviously require corrective actions. However as is shown by the operating deflected shape, the relative vibration between the base and centreline of the compressor frame is 0.5 ips pk (13 mm/s pk), which is within guideline. The skid vibration exceeds the design guideline of 0.1 ips pk (2.5 mm/s pk) and further analysis may be required to determine if the skid vibration is acceptable.

The issue of vibration guidelines gets more complex when there are multiple compressors on a common topside structure and the compressors are close to each other, such as the installation shown in Figure 7.

Figure 7: FPSO Design for Two 1000HP (746kW) Compressor Units on a Common Topside Structure

The vibrations from multiple units in close proximity will interact with other. The phase relationship between the two (or more) units will change with each start-up in the case of synchronous motor drive compressors, or be continuously varying in the case of induction motor drive or engine drive systems. A single forced response assuming a fixed phase relationship between the compressors may not necessarily determine the worst case condition. The conservative design approach is to conduct a separate analysis for each compressor package assuming it is the only unit operating and calculate a scalar addition of the vibrations from the separate simulations. An alternative approach for synchronous motor drive systems is varying the phase angle between the units in fixed increments and calculating the vector addition of vibrations at all locations to determine the worst case phase relationship. This step-wise analysis may need to be repeated if structural modifications are made to the module as modifications will change how the vibrations from the multiple units will add.

As with all engineering decisions, there are trade-offs to be made for selecting one guideline over another. A more stringent guideline will generally require more design effort, higher capital cost for material and labour to install additional structural components, and increased weight which can be a significant factor in some offshore applications. A too lenient vibration guideline could result in excessive maintenance due to premature failure of running components. Careful evaluation of the results from the dynamic analysis is necessary to balance these issues along with the vibration guideline.

There are other guidelines that can be specified for the dynamic analysis of reciprocating compressor installations on FPSOs or platforms. There are guidelines to avoid resonance which specify an interval between structural MNFs and frequencies of dynamic loads, typically 10% to 25%. A dynamic analysis and vibration guideline supersede this resonance guideline as the dynamic analysis calculates the vibration at resonance.

Stress guidelines and fatigue can sometimes be expressed as a design consideration for reciprocating compressor installations. API 618 Analysis M6 addresses dynamic stress from the dynamic loads that cause vibration of piping and vessels. Dynamic stress and fatigue in the topside structure are not typically an issue. The dynamic stress in the topside structural members is typically very small if the vibration guideline is met. The dynamic stress is typically well below fatigue criterion as specified by Maddox[2] and others.

5 Modelling Recommendations

The dynamic analysis of the compressor package and topside structure is done using finite element analysis (FEA). The accuracy of the FEA depends in large part on the accuracy of the finite element model. Accuracy of the model refers to not only dimensional accuracy but also using the proper mathematical formulations to accurately simulate the physical behaviour. Accurately simulating the dynamic response of a reciprocating compressor package and topside structure requires different modelling techniques than are typically used for static and quasi-static simulations.

5.1 Model Mesh Size

FEA involves breaking a structure into a series of smaller pieces (called elements) that can be mathematically solved to determine the overall structural response. The number and distribution of elements is referred to as the mesh size. It is typical for the engineering company conducting the structural analysis to evaluate the quasi-static response using a structural analysis program (STAAD, SACS, others). The structural model uses beam-type elements to model the structure using a single element between joints or connections within the structure, a mesh size of 1. This mesh size will give accurate results for static loads and deflections however a finer mesh (more elements) is required to accurately calculate the dynamic response. Typically a mesh size of 2 to 4 is recommended to accurately calculate the dynamic response, particularly for higher order modes. Figure 8 shows images of a portal frame finite element model showing different element meshes.

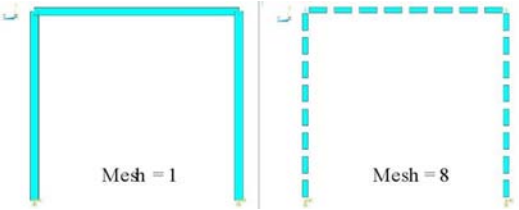

Figure 8: Finite Element Model of a Portal Frame

5.2 Mass Model

The way that the element mass is represented can also have a significant effect on the dynamic analysis results whereas the static results analysis results are typically not as sensitive to the element mass representation. Many finite element codes use a lumped mass approximation to simulate the beam weight. This means that the element weight is treated as 2 lumped weights at the ends of the beam. This can be an over-simplified model of the element mass, particularly for dynamic studies, that can introduce errors into the simulation results. Other finite element codes have an option to use a distributed mass element model. The distributed mass model is generally more accurate for dynamic analysis with a coarser mesh size compared to a lumped mass model.

Figure 9 and 10 show the effects of the mesh size and element mass properties on the calculated modal response and static response for the simple portal frame model shown in Figure 8.

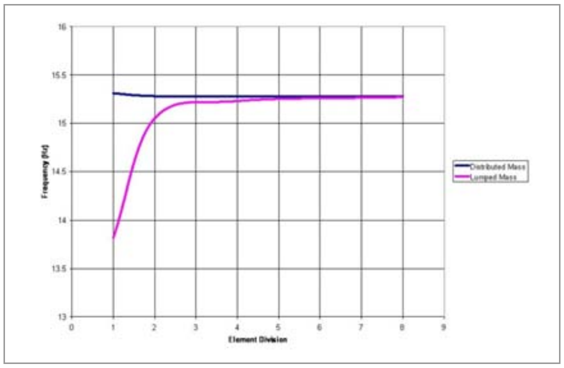

Figure 9: Effect of Mesh Size and Element Mass Formulation on the Calculated Mechanical Natural Frequency of a Portal Frame

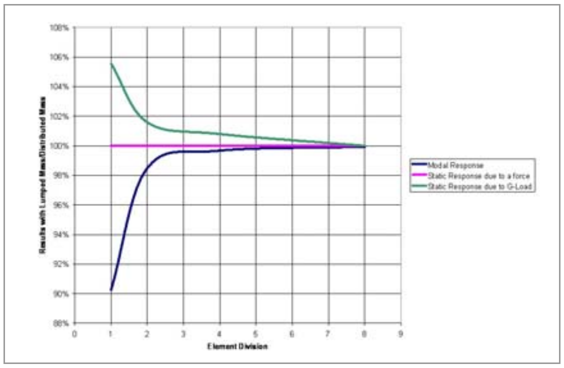

Figure 10: Effect of Mesh Size and Element Formulation Considering Different Loads and Analysis Types

5.3 Beam Element Warping

Another limitation in some finite element codes is that the beam elements do not have a warping degree-of-freedom. The warping degree-of-freedom controls the torsional response of the beams. A common method of modelling additional weight on a structure is to add several point masses on the deck beams. The point masses on the deck beams can result in spurious modes of the structure if the warping degree of freedom is not taken into account.

5.4 Reciprocating Compressor Package Model

The reciprocating compressor package must be modelled in sufficient detail so that the dynamic characteristics of the package are captured. The compressor package is sometimes represented as a single plate element or a simple frame of beam elements. These models are an overly simplistic model of the compressor package. The stiffness and mass characteristics of the package must be modelled so that the bending mode(s) of the compressor skid will be accurately calculated. The distributed weight effect of the compressor skid must also be included.

Many different methods can be used for connecting the reciprocating compressor package to the deck as long as proper analysis and design is done to ensure the dynamic response will be acceptable. The most common method of connection is welding the compressor skid to the deck beams. However, other methods such as antivibration mounts, gimbels, or stiff weldments at specific locations have also been used depending upon the application. Accurate modelling of the connection is key to calculating accurate results. Modelling a rigid point-to-point link between the compressor skid and the deck can, in some cases, concentrate loads when in reality the loads will be dispersed. Also, the connection model can add stiffness to the structure that will not in reality be there.

Accurate simulation of the compressor package and topside structure requires that the mass of the components mounted on the module are included. One method of simulating the effect of these components is by using a point mass at the centre of gravity of the component. This model of the component weight will accurately simulate the translational inertia effects of the component. There are often dynamic motions of the compressor package or topside structure that involve a strong rotational response of the component. Therefore, the rotational inertia of large components must be included. The rotational inertia can be included by specifying the characteristics in the point mass properties at the centre of gravity, or by simulating the mass distribution of the component. One challenge to the analyst is estimating the rotational inertia as this data may not be available from the manufacturer. Testing can be done on components in the compressor packager's fabrication facility to estimate the rotational inertia.

Some of the highest loads in a typical reciprocating compressor are unbalanced forces and couples from the reciprocating and rotating components in the compressor. These forces and couples are caused by the offset between the opposed compressor throws and the fact that the opposed throws are never perfectly balanced. One perceived advantage of 6 throw compressors is that because of the phase difference between the throws, the residual unbalanced forces and couples from each throw cancel and the resulting unbalance is very low. This cancellation of forces is based on the assumption that the compressor frame and crankshaft are rigid.

Detailed finite element modelling of the reciprocating compressor shows that the compressor frame is not rigid (see Figure 11). The compressor frame deflection due to the loads within the compressor frame can have a significant effect on the dynamic response of the compressor package and topside structure. A detailed model of the reciprocating compressor, be it a 2 throw, 4 throw, or 6 throw, may be necessary to conduct an accurate dynamic analysis.

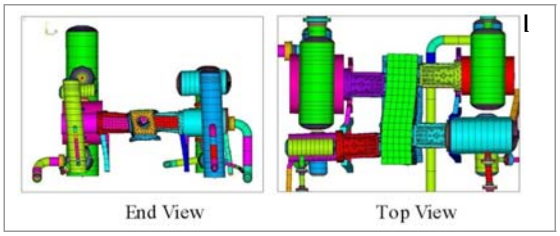

Figure 11: Four Throw Reciprocating Compressor Showing Frame Distortion Due to Normal Compressor Dynamic Loads

6. Case Study

The following is a case study that illustrates the example of the dynamic analysis of reciprocating compressors on a FPSO. The dynamic analysis included simulation of a single module on which three reciprocating compressors are mounted. The reciprocating compressors include:

- Two x MP compressors, 6 throw, four stage operation, 9.3 bar to 208 bar, 4815 HP (3590 kW), 718 RPM
- One x HP compressor, 2 throw, single stage operating, 205 bar to 286 bar, 915 HP (680 kW), 890 RPM

The three compressor packages were mounted on one module to allow for fabrication of the module and installation of the compressors on the dockside. The compressor packages and module were then lifted and installed as a single unit on the ship. The module also includes a central pipe rack and several process vessels.

A finite element model of the reciprocating compressor packages and topside structure was created with a commercial FEA program called ANSYS. The structural components were simulated in most part with beam elements. Shell elements were used for plate structures. The engineering consultant provided the model of the topside structure that was used for the quasi-static and lifting analysis. The model was created using the STAAD structural analysis software and converted to an ANSYS format by a custom translator created by the authors' company. Figure 12 shows plots of the finite element model of the module and reciprocating compressor packages.

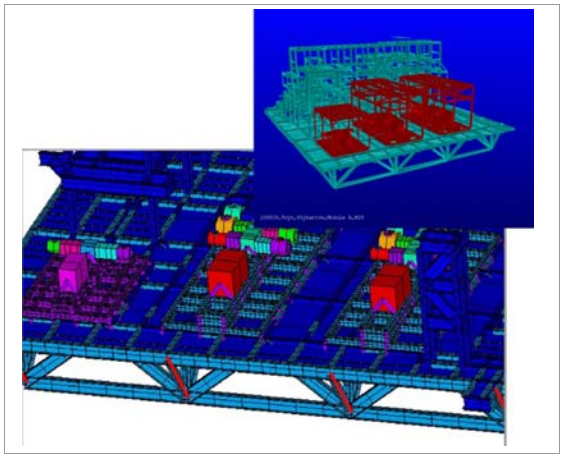

Figure 12: Images of the Module Finite Element Model

The dynamic loads in the reciprocating compressor as well as the unbalanced forces from pressure pulsations in the piping and vessels were calculated and applied to the finite element model. Post-processing software routines were used to extract and interpret results from the simulations.

Results from the dynamic analysis showed several areas with vibrations over the design guideline. Figure 13 illustrates typical results of the module dynamic analysis highlighting areas of high vibration. The module deck vibration design guideline was a particularly restrictive guideline, approximately 50% of Beta's standard guideline. Three different modifications were proposed to reduce vibrations to acceptable level.

- Diagonal bracing to stiffen the cantilevered edge around module.
- Diagonal bracing to stiffen the top deck underneath the compressor.
- Increased beam sizes in selected locations (near edges of compressor).

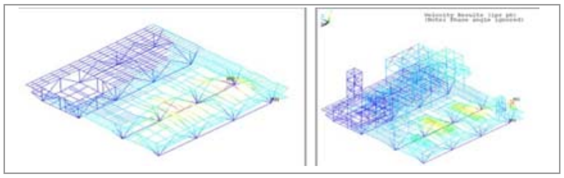

Figure 13: Dynamic Analysis Results for a Module Supporting Multiple Compressor Packages. Areas of yellow and red indicate marginal to high (over guideline) vibration.

The final design included a combination of the various modifications. Also, although the module deck vibration guideline could not be met in all locations, the design was considered acceptable.

The dynamic stress was found to be well within guidelines and the areas with vibrations over the design guideline were restricted to a very small area of the module and were not significant. The calculated vibration was a conservative estimate, as the vibration from all units were combined in a worst case. Vibrations will likely be lower for much of the compressor operation. It should be noted that some compromise between the module design and the vibration guidelines is sometimes necessary because of the limitations in the modifications that can be made to the module. Input by the engineering consultant doing the dynamic analysis early in the project is key to minimizing vibrations. Some basic considerations such as location of the reciprocating compressor packages relative to the module main structural members and support columns to the ship web frame can have a significant impact on the dynamic response. Often these design decisions are made at an early stage before the machinery consultant is involved.

7. Recommendations for Specifying Dynamic Analysis Studies

The following recommendations are made for specifying dynamic analysis studies of reciprocating compressor on FPSO topside modules:

- The dynamic analysis must be conducted by an engineering firm with specialized knowledge of the reciprocating compressor dynamics. The analysis must include detailed dynamic simulation of the reciprocating compressor and the topside module.
- It is important for stakeholders to meet and agree on scope, methodology, and guidelines early in the design process. Stakeholders include owner, engineering consultant(s), and compressor packager.
- The design of the reciprocating compressor package and the topside structure should be conducted in parallel so that an optimal design can be determined to minimize the dynamic response.
- We recommend that the engineering firm that conducts the topside dynamic analysis also conducts the detailed reciprocating compressor dynamic studies that are applicable (API 618 studies). This approach will minimize engineering time and avoid conflicts in the compressor package design, vibration limits, and design recommendations.
- The engineering consultant conducting the detailed design of the topside structure for static and quasi-static loads should supply the computer model to the consultant conducting the dynamic analysis. This significantly reduces the amount of work and end user costs for the dynamic analysis.
- Details of the dynamic analysis must include:
    - The dynamic loads that include the unbalanced forces and moments, crosshead guide forces, gas rod load forces, pulsation induced forces in key piping and vessels, and unbalanced forces in the motor or engine.
    - Simulation results at the first and second orders of compressor speed as dynamic loads are the highest at these frequencies. Analysis at higher orders of compressor speed may be necessary in some cases such as an engine drive or where significant acoustical forces exist.
    - Calculated vibration on the structure, compressor skid, and major components mounted on the compressor package such as the compressor frame, compressor cylinders, driver, and major vessels. The calculated vibrations will be compared to industry guidelines for the different components.
    - A topside finite element model that includes a representative stiffness for the ship deck and web frame at the topside structure’s stabbing points.
    - A final report that includes recommendations for the reciprocating compressor package design and/or topside structure design as well as a summary of the applied loads and results (calculated mode shapes, mechanical natural frequencies and vibration amplitudes).

8 Summary

A growing number of reciprocating compressors are being installed in offshore applications. Owners and engineering companies should consider a dynamic analysis of the production structure when high power reciprocating compressors are employed (i.e., over 500 HP (370 kW)). The paper outlines recommended specifications to include in tender documents and other tips to improve the design, construction, and long term operation of reciprocating compressor packages for offshore applications.

References

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2. Maddox, S.J.: ‘Fatigue Strength of Welded Structures’ 2nd Edition, Abington Publishing, Cambridge, 1991