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An establishment of a digital storehouse based on ROM, FBS and RPA technologies for the rapid design of low-vibration marine engines

Simulation Technologies, Digital Twins and Complex System Simulation

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ABSTRACT

Since the launch of the H21/32 HiMSEN engine in 2001, HD Hyundai Heavy Industries has continuously developed diesel, gas, and dual-fuel engines with various bore sizes. Recently, in response to GHG regulations, the company has been leading the global trend of carbon-neutral engines. This effort began with the world's first type approval of the 4-stroke, 32-bore methanol engine (H32DF-LM) in 2022, and development is ongoing for next-generation zero-carbon fuel engines, including ammonia and hydrogen. As the market for carbon-neutral engines rapidly expands, shipbuilders increasingly demand safer and more reliable engines, pushing engine manufacturers to overcome the limitations of existing design technologies. In response, HD Hyundai Heavy Industries is addressing these challenges through advanced virtual product development technologies.

This paper introduces a quick and accurate simulation methodology based on Reduced Order Models (ROM), Frequency-Based Substructuring (FBS), and Robotic Process Automation (RPA) to predict engine vibration performance, a critical factor in ensuring the structural safety of engines and their attachments. Furthermore, the paper outlines a systematic and integrated simulation platform roadmap, including the establishment of a Digital Warehouse, to propose future technologies for engine manufacturers.

1 INTRODUCTION

Since the launch of the H21/32 HiMSEN engine in 2001, HD Hyundai Heavy Industries has continuously developed diesel, gas, and dual-fuel engines with various bore sizes. Recently, in response to GHG regulations, the company has been leading the global trend of carbon-neutral engines. This effort began with the world's first type approval of the 4-stroke, 32-bore methanol engine (H32DF-LM) in 2022, and development is ongoing for next-generation zero-carbon fuel engines, including ammonia and hydrogen. As the market for carbon-neutral engines rapidly expands, shipbuilders increasingly demand safer and more reliable engines, pushing engine manufacturers to overcome the limitations of existing design technologies. In response, HD Hyundai Heavy Industries is addressing these challenges through advanced virtual product development technologies.

Figure 1. Development history of the HiMSEN engine.

The prediction of dynamic characteristics in marine engines is of critical importance. However, these characteristics can only be confirmed during the Factory Acceptance Test (FAT), which can sometimes lead to significant issues. If issues arise at the final stage, they lead to significant cost and time consumption with minimal flexibility for design modification. Therefore, it is essential to predict and evaluate the dynamic characteristics of engines during the basic design stage.

High-fidelity Computer-Aided Engineering (CAE) is crucial for quantitatively predicting and evaluating dynamic stability during the basic design stage. However, Finite Element Method (FEM) requires significant computational time due to the large number of degrees of freedom needed to ensure analysis reliability. This issue becomes even more pronounced during the design iteration in the basic design stage, which extends evaluation times and increases the complexity of analysis. Consequently, reducing analysis time is crucial for achieving optimal design. Furthermore, make-to-order such as marine engine, The stiffness and inertia of components such as engines, generators, and resilient mounts vary for each project. Due to these differences in design, there is a potential risk to dynamic characteristics. However, Due to limited resources, it is not feasible to perform analysis and evaluation for every project.

In this study, a Reduced Order Model (ROM) was developed for 4-stroke marine engine gensets to reduce analysis time and ensure reliability. Using the massive design data of HiMSEN engine, potential risk management was conducted, along with trend analysis of design data and the implementation of a tolerance design. Additionally, a data-driven prediction methodology is proposed through the establishment of a Simulation Process and Data Management (SPDM) system with 1-D ROM analysis data and big data on the design of the HiMSEN engine since its initial production in 2001.

2 REDUCED ORDER MODEL

The first study established a vibration prediction process that reduces analysis time and product development cycles using the ROM technique. A ROM modeling and analysis procedure was developed based on in-house code, and its accuracy was verified by comparison with FEM results. Additionally, a vibration contribution analysis for each component was conducted.

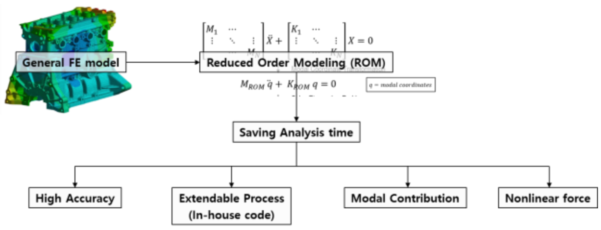

Figure 2. Advantage of Reduced Order Modeling technique

2.1 Theory

The Component Mode Synthesis (CMS) method is one of the most representative techniques of dynamic sub-structuring. It is a method where the analysis model is decomposed into components, each analyzed individually, and the results are re-synthesized. Unchanged components do not require re-analysis during the design iteration, and only the design space is analyzed and integrated into the results. This approach significantly reduces analysis time compared to the full model, and this reduction analysis process is referred to as the Reduced Order Model (ROM).

In the ROM model, the Transform Matrix (T) is composed of the Normal Mode (ϕ) and the Constraint Mode (ψ). The Normal Mode (ϕ) is determined by the Degrees of Freedom (DoFs) of the internal nodes, which are defined by the non-design space. The Constraint Mode (ψ) is determined by the DoFs of the boundary nodes, which include the design space, as well as interface, forcing, and sensing nodes. Using the constructed Transform Matrix (T), the governing equation of the linear vibration system is converted from the physical domain to the modal domain. In this process, the Normal Mode (ϕ) derived from the internal nodes is expressed in modal coordinates, allowing a significant reduction in the number of DoFs.

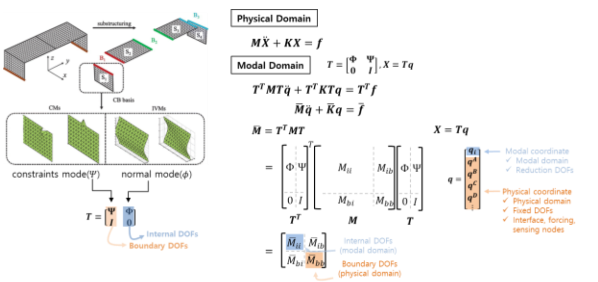

Figure 3. Theory of Component Mode Synthesis

2.2 Target Model

The ROM modeling was constructed for the 12H3240V generator set. The 12H3240V is a vee-type engine with a bore size of 320 mm, a stroke of 400 mm, 12 cylinders, and a bank angle of 50 degrees. Its rated RPM is 720 RPM, output power of 6 MW. The genset (generator set) consists of an engine, generator, baseframe, and shaft, etc. In recent carbon neutral engines, high-inertia auxiliary parts such as high-pressure pumps are increasing, and these components can also be separately modeled using the ROM approach.

Table 1. Specification of 12H3240 Generator set

Type : 12H32/40V Generator set	
Cylinder no.	12
Bore	320mm
Stroke	500 kW/cyl.
Speed	720rpm
Bank angle	50 degree

2.3 Modeling process

The ROM process is implemented using MATLAB-based in-house code, while the mass and stiffness matrices for the 3D model are automatically computed by invoking a FEM solver.

The first step is the sub-structuring stage, where the system is divided into several parts.

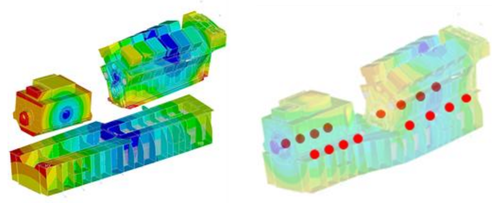

Figure 4. Applying Sub-structuring technique for 4-stroke marine engine

The second step is defining the Degrees of Freedom (DOFs) for internal nodes and boundary nodes. Internal nodes represent the dynamic behavior of the separated components and correspond to the normal mode (ϕ) described in Section 2.1. Boundary nodes include interface nodes, sensing nodes, and forcing nodes, which correspond to the constraint mode (ψ), as explained in Section 2.1. Notably, boundary nodes cannot be reduced. So, components must be separated in a way that minimizes interface nodes. Next, the normal modes and constraint modes of each separated component are extracted. These calculations are performed using in-house code with commercial solvers such as Abaqus or Ansys. Finally, the extracted mass and stiffness matrices are coupled and synthesized to derive the final response. Figure. 5 shows this process in a schematic representation.

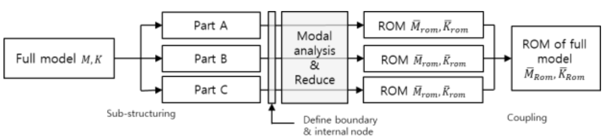

Figure 5. Process of Reduced order modeling

2.4 Validation

2.4.1 Comparison of natural frequency

Validation was performed using commercial solvers such as Abaqus and Ansys. The natural frequencies of the ROM model were compared with those of the FEM model. The maximum error in natural frequency between the FEM and ROM models was found to be only 0.24%.

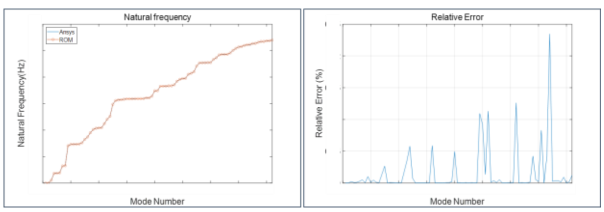

Figure 6. Validation of Natural frequency and relative error

2.4.2 Comparison of forced vibration response

The main excitation forces acting on the engine are cylinder pressure, cylinder wall force, and bearing force. The harmonic excitation forces corresponding to these loads are calculated using in-house code and mapped onto the FE model. We carried out Time Domain Analysis (TDA) both the FEM and ROM models, and their steady-state responses were compared in the time domain and frequency domain. Additionally, to further reduce analysis time in the ROM model, the excitation forces were converted to the frequency domain, and Frequency Response Analysis (FRA) was performed. It is shown that the maximum and the average error are within the acceptable range.

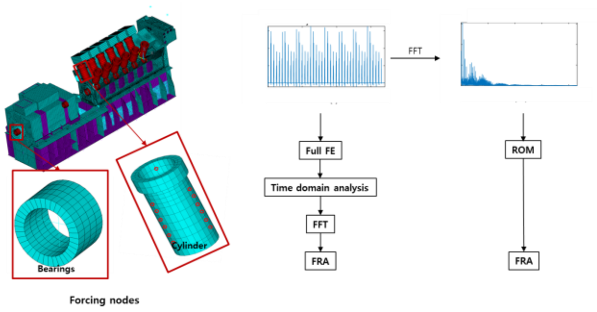

Figure 7. Excitation force of 4-stroke marine engine

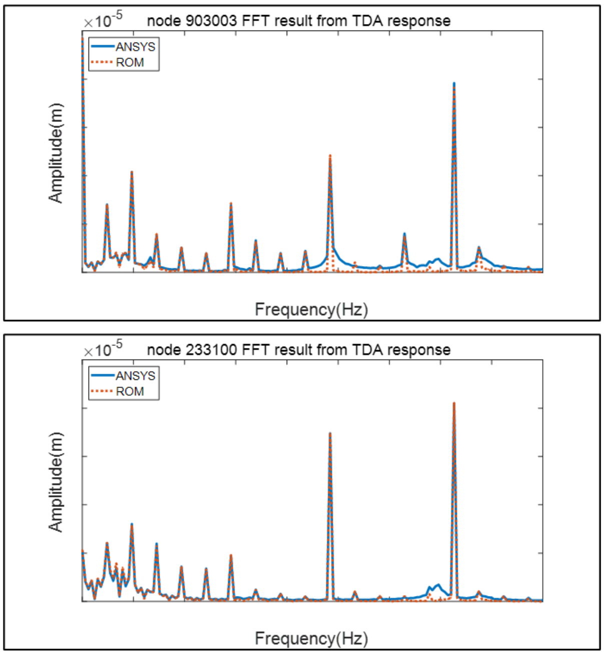

Figure 8. Vibration response error between FEM and ROM

2.5 Application

Using the ROM, it is possible to derive design solutions for high vibration components during the basic design stage while minimizing analysis iterations. By re-analysis only the design space and excluding the non-design space, iteration time is significantly reduced, enabling response predictions for design changes within seconds. Additionally, the reduced computation time allows for the identification of the optimal support stiffness and location.

In the example engine, it was observed that significant vibrations occurred at the Engine T/C support, necessitating reinforcement with optimal positioning and stiffness. The response was found to be pronounced in the 20–30 Hz frequency range, and a reinforcement beam was designed with optimal location and stiffness to control the corresponding mode. Despite the model containing over 2 million elements, the analysis could be conducted within seconds, enabling efficient and effective design optimization.

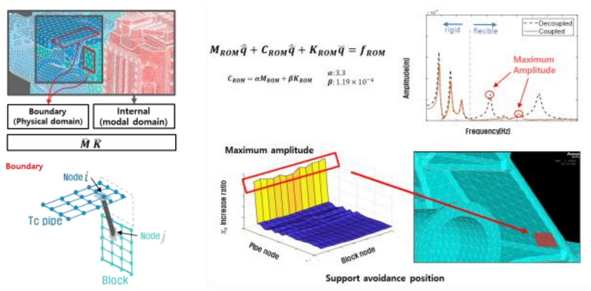

Figure 9. Support beam optimization using ROM

2.6 Results

A Reduced Order Model (ROM) was developed for the rapid dynamic response prediction of a 4-stroke marine engine. The accuracy of the ROM model was verified to be within the acceptable range. Additionally, the analysis time reduced by up to 98% compared to FEM.

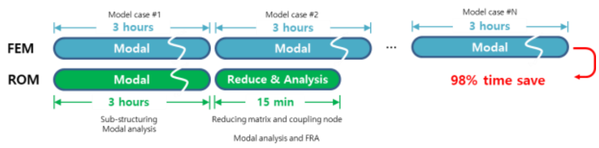

Figure 10. Support beam optimization using ROM

3 ROBOTIC PROCESS AUTOMATION

The second study established a system that detects potential high-vibration risks using Robotic Process Automation (RPA) and massive design data and notifies designers accordingly. The process of RPA, the classification of dynamic characteristics index, and operating cases are introduced.

3.1 Concept of RPA

The HiMSEN engine has achieved a cumulative production of over 15,000 units. However, due to its make-to-order production approach, each design is distinct. The design data for all engines is uploaded as drawings to the system, and the performance, including vibration, is added to the database through conducting the Factory Acceptance Test (FAT). By linking this vibration performance data with the associated design parameters, it becomes possible not only to anticipate the risk of high vibration in new designs through trend analysis but also to predict vibration performance.

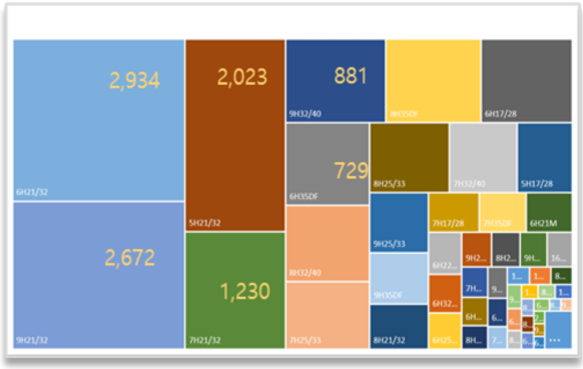

Figure 11. Cumulative Production Volume of HiMSEN Engine

3.2 Representative index of dynamic specification

There are numerous design parameters, but not all are related to dynamic characteristics. The most critical aspect of the RPA system is the selection of reasonable parameters and the establishment of criteria based on domain knowledge. We identified representative indices that are analyzed the design trends of 15,000 engines for these indices. Figure 12 shows the distribution of actual design data for one of these variables and the corresponding criteria.

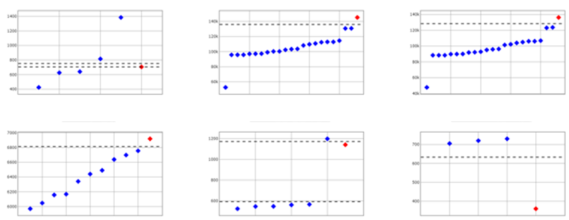

Figure 12. Design point about vibration index of HiMSEN genset

4 DIGITAL STOREHOUSE OF VIBRATION DATA

4.1 Concept of digital storehouse

The fundamental concept of the Digital Storehouse is to select, classify, and store meaningful vibration data in a 1-D format, enabling instant access and review when needed. Furthermore, it allows for the prediction of results in new design domains using the stored data. This approach is also referred to as Simulation Process and Data Management (SPDM). Our goal is to establish a vibration Digital Storehouse that integrates the simulation-based 1-D model (ROM) and the mass-production design 1-D data (RPA) constructed above.

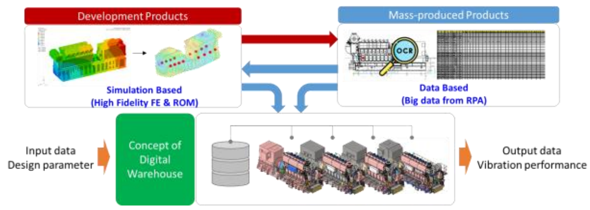

Figure 14. Concept of digital storehouse

4.2 Effect of digital storehouse

With the advent of the carbon neutral engine market, the pace of product development is accelerating to secure market dominance. Accordingly, it is essential to enhance simulation speed, and the adoption of the Virtual Product Development (VPD) methodology has become indispensable.

By utilizing Simulation Process and Data Management (SPDM) to structure vibration design data and simulation data into a database (DB), the accuracy and efficiency of vibration assessments can be significantly improved. Firstly, systematic management of simulation results for various engine types facilitates data comparison and analysis. Secondly, leveraging accumulated simulation and design data enables the early identification of potential resonance risks during the design phase and supports the derivation of optimal design strategies. Thirdly, analyzing historical data on similar vibration issues reduces problem-solving time and allows for the prediction of vibration characteristic changes during design modifications by incorporating regression analysis and machine learning techniques. Finally, data-driven automated vibration analysis and optimization enhance not only the efficiency of the product development cycle but also the consistency and quality of vibration performance.

5 CONCLUSIONS

This study undertook a comprehensive approach to enhance the efficiency and reliability of dynamic stability evaluations for 4-stroke marine engine gensets. The primary goal was to address the limitations of traditional Finite Element Method (FEM), particularly the significant computational time and complexity encountered during design iterations. By developing a Reduced Order Model (ROM), analysis time was significantly reduced while maintaining the accuracy and reliability of the results. The ROM was validated through comparisons of natural frequencies and forced vibration responses, demonstrating excellent alignment with high-precision FEM results.

Furthermore, the integration of Robotic Process Automation (RPA) greatly improved the efficiency and consistency of data collection. The Simulation Process and Data Management (SPDM) system and the digital storehouse of vibration data are currently in the development stage. Their expected benefits include the potential for data-driven predictive methodologies utilizing design parameter data automatically collected by RPA and 1-D ROM analysis data. Additionally, the dashboard alarm system based on dynamic specification indices shows potential as a proactive monitoring mechanism to improve decision-making processes during the design stage.

The digital storehouse of vibration data is expected to contribute to the structured management and utilization of historical data. This digital infrastructure can simplify data accessibility and support advanced trend analyses, providing valuable insights for future design improvements.

In conclusion, the methodologies and systems developed in this study have proven effective in reducing analysis time, enhancing reliability, and optimizing dynamic stability evaluations for marine engine gensets. Future research may focus on expanding the application of ROM to other engine types, improving RPA algorithms for broader data collection, and further developing SPDM systems and digital storehouses to support predictive maintenance and real-time monitoring capabilities.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

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7 REFERENCES AND BIBLIOGRAPHY

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8 CONTACT

This is where the main author information is given, if desired, such as background, education, e-mail address, and web address. This is an optional section.

9 PAPER SUBMISSION

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