MHI's High-Performance and High-Reliability Products Enabled by Algorithmic Design

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Throughout its long history, Mitsubishi Heavy Industries, Ltd. (MHI) has provided reliable products with high-performance to the world across 30 business domains. Today, as each product becomes established and global competition intensifies, a unified design platform that mutually shares the strengths of these independent businesses is essential to further enhance product value. However, realizing such a platform has been difficult up to now due to differences in shape definition and modelling methods between products. To address these challenges, MHI has developed algorithmic design technology that can generate 3D shapes using flexible shape definition algorithms and optimize product shapes in coordination with analysis, leading to improvement in product value in the infrastructure, energy, and transportation fields. This report presents the advantages of this platform and case studies of implementation.

1. Introduction

As a conglomerate with a long history and 30 business domains, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) possesses product development expertise and a proven track record across thousands of products [(1)]. In addition to sharing and standardizing development processes across its products, MHI is pursuing efforts aimed at further enhancing product value through an optimized design process capable of handling a wide range of components across multiple technical fields.

As shown in **Figure 1**, MHI has been promoting cross-domain collaboration in recent years, such as establishing a Shared Technology Framework and Innovative Total Optimization (ITO) [(1)]. However, in the product development process, differences in shape definition and modelling methods between products have become issues which make covering MHI's broad product portfolio solely by commercially available design platforms difficult. Requirements for the design platform include the following.

- Integration of internal and external analysis tools that have been validated over many years
- Flexible shape definition and 3D model generation regardless of product type or complexity
- Analysis using multiple physical models including fluid mechanics, thermodynamics, structural mechanics, and vibration mechanics
- Compatibility with the product development process, and completion of design review within a few months.

To address these challenges, MHI has developed a design platform utilizing algorithmic design. Originally developed for the architectural field, algorithmic design faithfully reproduces shapes from point (0D) to volume (3D) data using user-defined algorithms and directly converts 3D models into inputs for analysis tools through labeling (**Figure 2**). To develop algorithmic design workflows, the Rhinoceros/Grasshopper environment by Robert McNeel & Associates [(2)] was used.

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This platform is applicable to a wide range of products, such as turbomachinery, ships, and drones, and can be used in coordination with analysis processes utilizing multiple physical models. Representative examples of its application to MHI's design process are shown in the following sections.

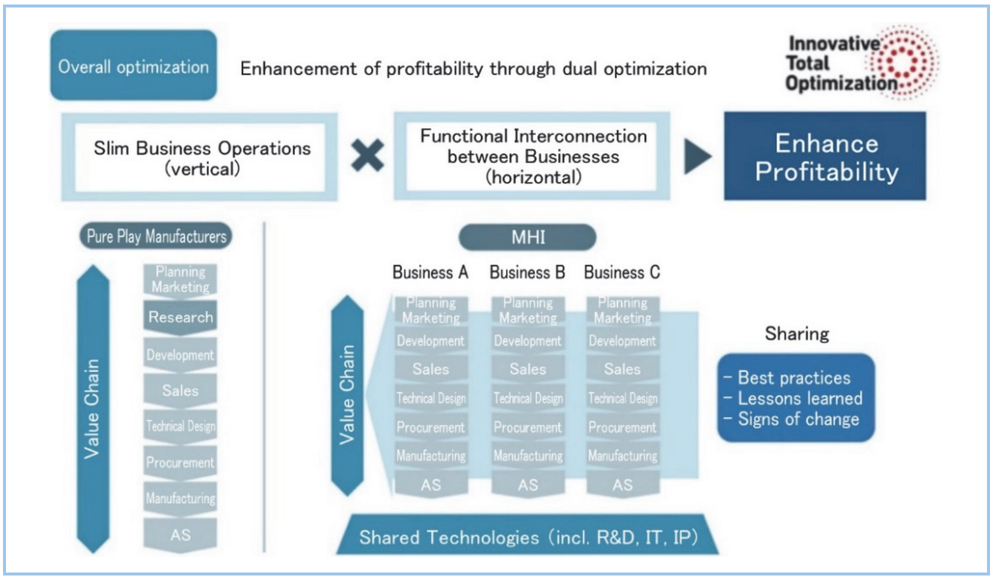

Figure 1 Product value enhancement by ITO

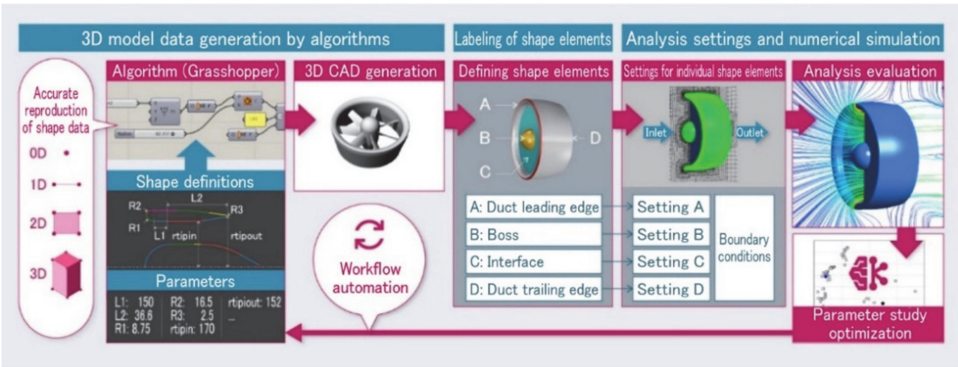

Figure 2 Algorithmic design workflow

2. Automation of labor-intensive complex product shape definition

The shape of a ship's hull is composed of three-dimensional free-form surfaces, with complex specifications.

MHI's conventional method to generate hull shape involves manually adjusting the position of a large number of control points that define freeform surfaces. Consequently, a significant amount of time is required for shape definition, which limits the number of optimization cases that can be evaluated by CFD analysis within the limited development period. To address this challenge, a process for hull shape definition that utilizes algorithmic design has been established.

The developed process defines hull shape using several dozen parameters that represent the shape of the bow and stern, in addition to key hull dimensions such as overall ship length, beam, and draft (**Figure 3**). By incorporating MHI design expertise, hull shapes that satisfy design requirements such as displacement can be generated.

Figure 4 compares the time required for hull shape definition and CFD analysis results for designs generated by the conventional method and by algorithmic design.

Time required to create hull shape using algorithmic design is approximately 80% less than conventional methods. Furthermore, according to the CFD analysis results, no significant differences in wave height distribution characteristics (such as height and distribution form of waves generated by the bow and stern, and the angle of waves generated at the bow) between the two designs are observed, providing the prospect of replacing conventional tools with algorithmic design.

Based on the above, a path that contributes to broader and faster exploration of hull shapes that maximize propulsion performance by using algorithmic design has been established.

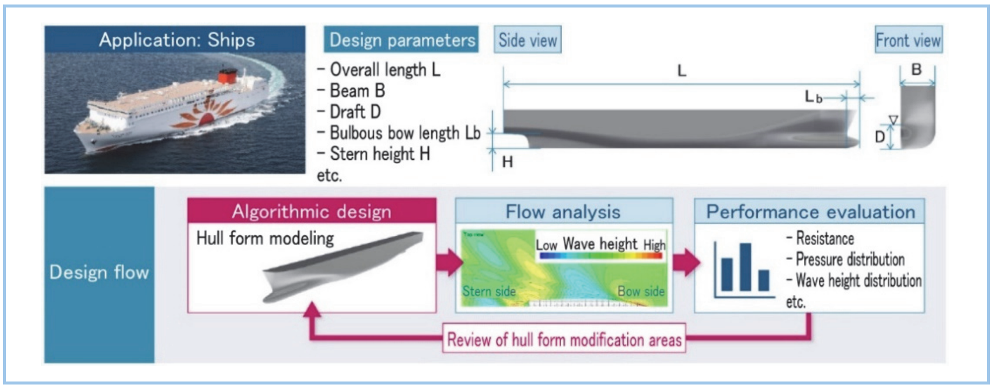

Figure 3 Rapid hull shape definition using algorithmic design

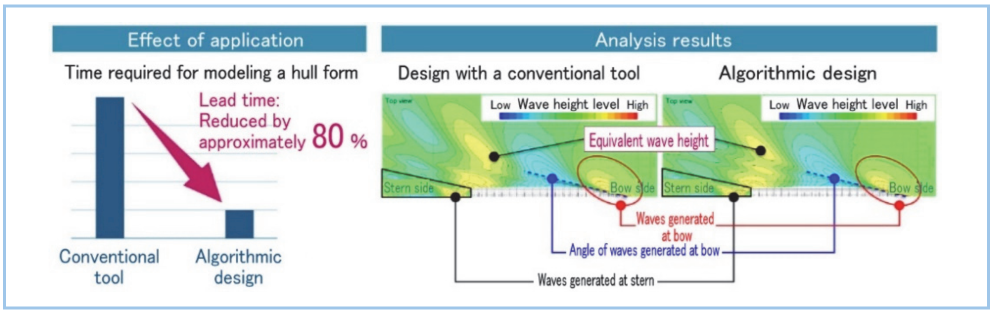

Figure 4 Reduction in hull form design lead time with algorithmic design

3. Improvement in overall efficiency of multiple components

One measure to prevent efficiency degradation due to leakage from the gaps between rotating and stationary components in turbomachinery (such as power generation gas turbines, steam turbines, aircraft engines, and industrial centrifugal compressors) is the honeycomb labyrinth seal, which consists of a labyrinth seal on the rotating side and a honeycomb land installed on the stationary side. The honeycomb land is employed to ensure strict clearance control, weight reduction, and high durability against wear during operation.

Modeling the honeycomb land is time-consuming due to its complex shape, and therefore, cases [(3)] where its shape was simultaneously optimized with the matching labyrinth seal from the perspective of improving aerodynamic performance are limited. However, a previous in-house case study [(4)] of such optimization was generalized by algorithmic design and expanded to other products. By parametrically defining the shapes of both the labyrinth seal and the honeycomb land and performing CFD analysis on a vast number of combinations, an optimal shape could be determined (**Figure 5**).

Leakage flow rate of the optimized shape shown in **Figure 6** is reduced by 21.7% compared to the base shape. Characteristics of the optimized shape include fin thickness approximately five times the seal clearance, honeycomb cell width slightly smaller than the fin thickness, and slanted cells.

The leakage reduction mechanism of this design can be explained by the following three points:

- Increased fin thickness ensures that each fin imposes more than twice the number of flow contractions.
- Enlarged honeycomb size increases the distance between flow contractions, providing sufficient length for the leakage jets from the upstream fin to decelerate before reaching the downstream fin.
- The slant of the honeycomb cell captures leakage flow within the cell, inducing flow separation downstream of the cell, thereby amplifying flow contraction.

In this way, by incorporating algorithmic design, the shapes of multiple components are simultaneously optimized to minimize leakage and achieve high efficiency.

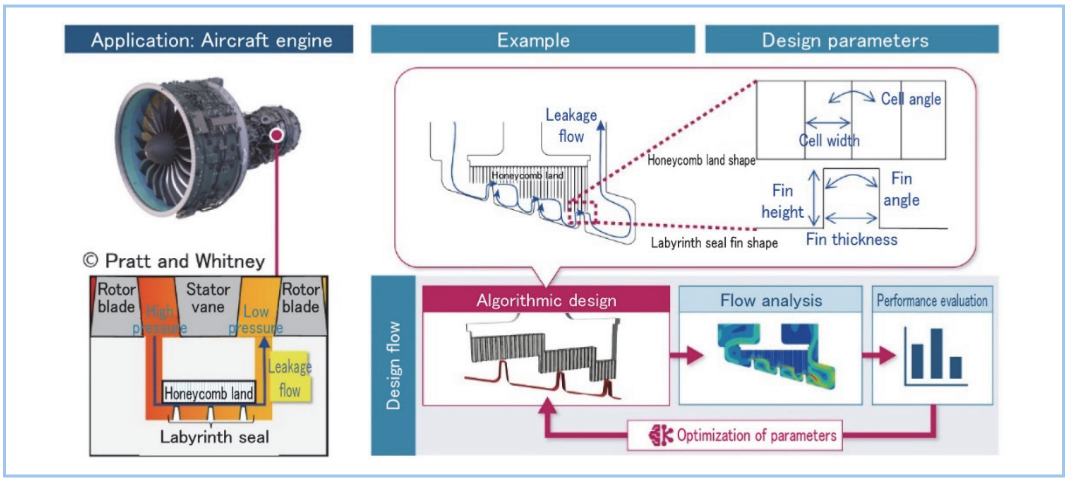

Figure 5 Simultaneous optimization of labyrinth seal fin shape and honeycomb land shape using algorithmic design

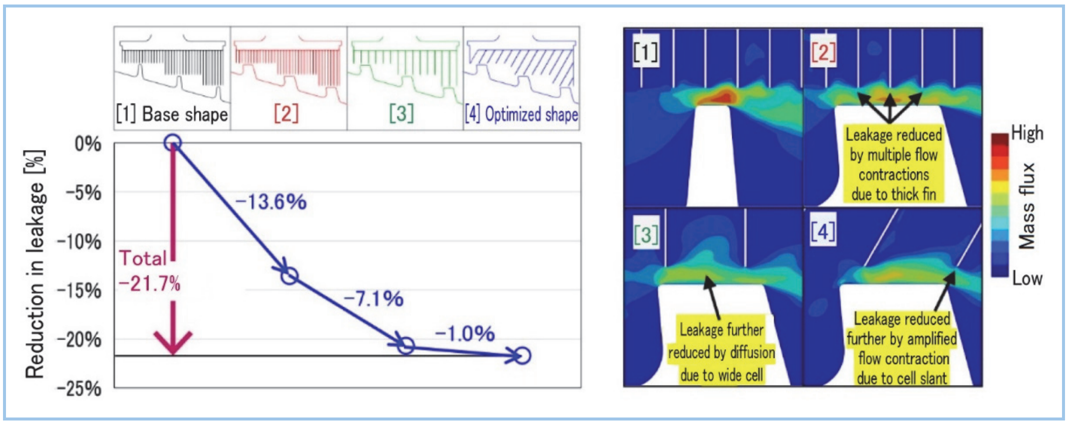

Figure 6 Leakage reduction mechanism of simultaneously optimized shapes

4. Evaluation of aerodynamics and blade vibration strength for axial turbine blade shape and exhaust casing

In the marine turbocharger industry, competition on performance has intensified against the backdrop of heightened economic expectations for the adoption of new fuels. Consequently, improving not only rotating components such as blades but also stationary components with complex three-dimensional shapes has become important. Furthermore, structural requirements such as vibration strength must be met at all resonance points within the operating range, with the goal of satisfying the established criteria.

In conventional design, manual tasks such as 3D model development create a bottleneck, preventing sufficient efforts toward shape optimization. In response, algorithmic design is applied to model the rotor blades and exhaust casing of a marine turbocharger axial turbine rapidly and automatically. Specifically, rotor blade throat distribution and diffuser shape are optimized to increase overall efficiency under low-load conditions where performance improvement is crucial, and the stator vane shape was optimized to minimize vibration stress in higher-order modes (**Figure 7**).

Optimization results are summarized in **Figure 8**. Overall efficiency under low-load conditions improves by 0.49% compared to the base case. The optimum rotor blades show a W-shaped throat distribution which increases flow velocity at the end wall and suppresses separation, leading to uniform deceleration within the diffuser section where the area ratio increases. This maximizes static pressure recovery in the diffuser section, leading to improvement in overall efficiency [(5)]. Furthermore, regarding vibration strength, excitation force is suppressed with an intake-side lean and inverse-bowing of the stator vanes, reducing vibration stress from problematic modes by up to 78%. This occurs as the exit angle increases at the mid-span height of the stator vane, widening the gap with the metal angle, and reducing the peak Mach number, thereby suppressing primary excitation sources, shock waves and wakes.

In this way, by simultaneously evaluating aerodynamic performance and vibration strength for a vast number of shapes generated by algorithmic design, rapidly designing products that achieve both high efficiency and high reliability has become possible.

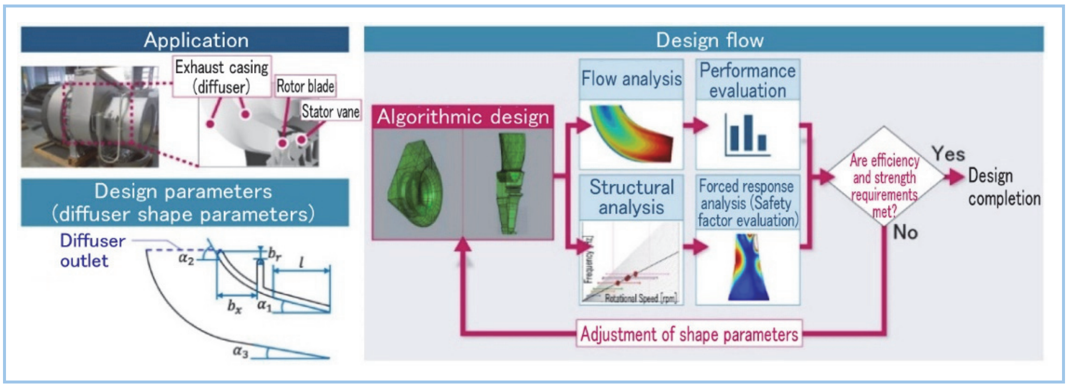

Figure 7　Simultaneous optimization of marine turbocharger turbine and exhaust diffuser using algorithmic design

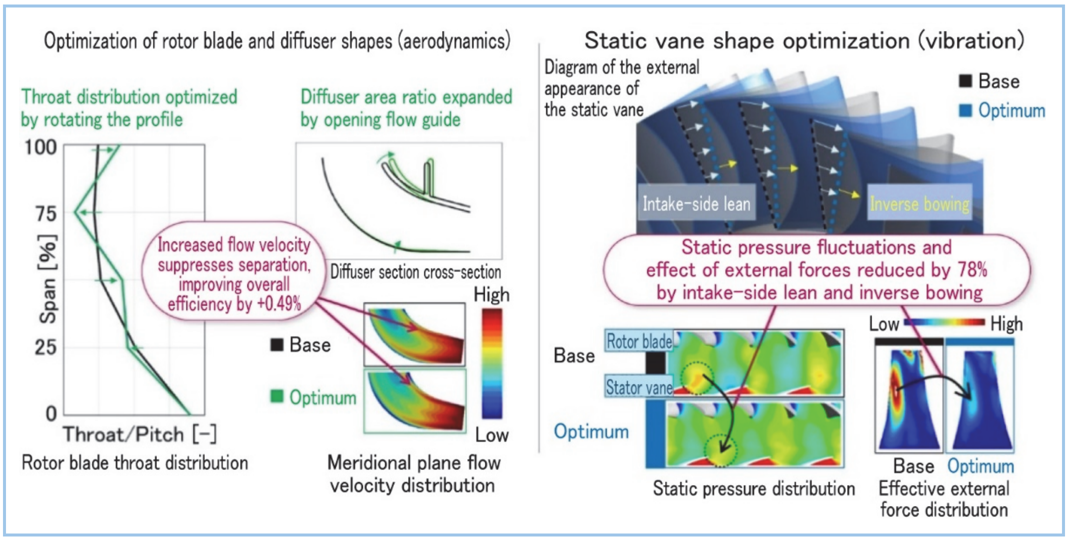

Figure 8　Results of simultaneous optimization of aerodynamics and vibration strength

5. Application to new product development through agile methodology

In today's rapidly changing market environment, development of new products and technologies that respond quickly and flexibly to market needs is required. Consequently, it is important to adopt a product development process using an agile methodology that enables smaller, faster hypothesis verification cycles.

MHI has proposed, as a new product, an industrial drone to assist or replace human workers performing high-altitude work on steel towers, bridges, and similar structures, with a propulsion system configuration that features a ducted fan, based on a compact, high-thrust, and highly safe design concept. MHI is currently conducting research and development for its Proof of Concept (PoC). This drone can operate under various conditions, including hovering in no-wind (stationary position in the air) or crosswind conditions, and in descent conditions. As a result, a process utilizing algorithmic design to generate duct shapes based on design parameters and CFD analysis to evaluate performance under various conditions was established to optimize the shape, resulting in a robust, high-performance duct shape (**Figure 9**).

Consequently, compared to the initial shape, the optimized shape exhibits a 13% reduction in lateral force, with a 1% increase in thrust under no-wind conditions. A comparison of flow fields under crosswind conditions, where significant improvements are observed between the initial and optimized shapes is shown in **Figure 10**. As shown in the velocity distribution, the initial shape exhibits a strong negative pressure region at the duct lip, where rapid acceleration followed by sudden deceleration occurs, causing flow separation on the inner circumferential side of the lip.

This generates lateral drag, leading to an increase in lateral force. On the other hand, the optimized shape features a thicker duct lip with less curvature which reduces the local negative pressure region, which in turn moderates flow acceleration and deceleration and eliminates the separation region. As a result, a significant reduction in the lateral force is achieved [(6)]. Based on this optimized shape concept, a prototype drone was constructed and outdoor flight tests were conducted, confirming stable flight and feasibility of the concept.

For new product development such as this, rapidly executing hypothesis-verification cycles is important. Utilization of the algorithmic design is confirmed to be effective for this purpose.

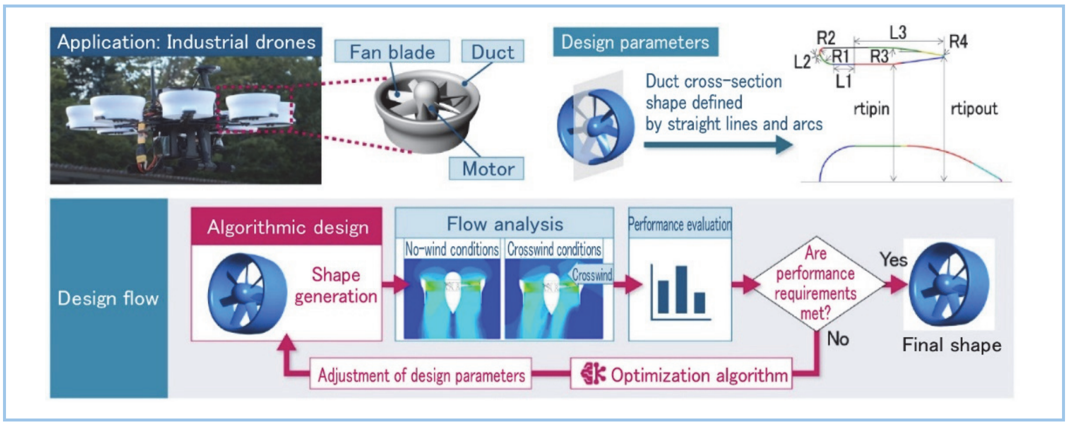

Figure 9 Agile development of industrial drone using algorithmic design

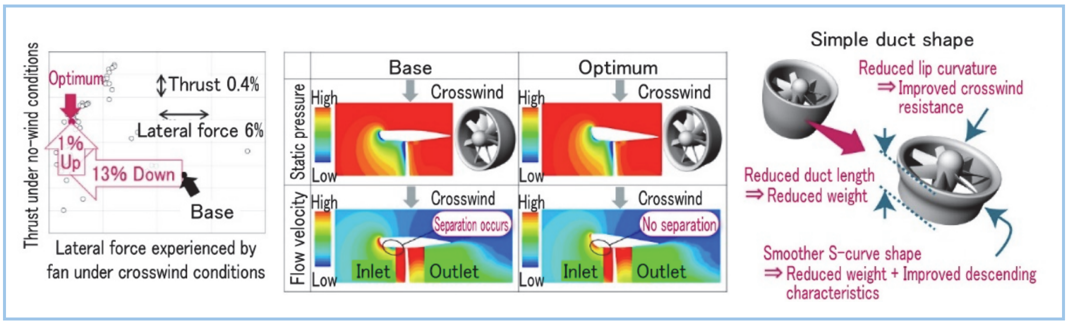

Figure 10 Ducted fan for industrial drones optimized for multiple operating conditions

6. Conclusion

The introduction of algorithmic design has enabled the enhancement of product value for infrastructure, energy, and transportation products within their development cycles. Furthermore, optimization through the simultaneous consideration of multiple metrics is made possible by combining multiple dynamics models. MHI will broaden the application of this technology to the development of various products and combine the strengths of even more products to create high-performance products that deliver maximum value to customers.

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