A Study of Morphological Design in an Industrial Vertical Multistage Pump

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Abstract
The objective of this study is to apply a morphological design, developed by JAXA Dynamics Design Team, into an industrial multistage vertical pump, and to confirm the effect of the Morphological design. In order to apply the morphological design in the industrial design, the tradeoffs between cost, performance and reliability are very important. The result of the morphological design in the industrial pump shows the decrease in the cost, the improvement of the hydraulic performance and the reliability compared with the ordinary design pump. It has been confirmed that the morphological design process proposed in this study is suitable for industrial multi-stage pumps.

Keywords: Pump, Design, Design optimization, Vibration, Performance improvement, Morphological design

1. Introduction
When turbomachineries such as pumps and compressors has used in the present-day industrial world are designed, the design of impellers and stationary components such as casing and diffuser are generally determined first in order to maximize efficiency and the detailed design of mechanical components of the bearing, seal, and rotor portions is carried out subsequently. Machines that are designed in the abovementioned order have few parts that can be corrected in a problem (e.g. excessive vibration occurrence). For that reason, only short-term solutions are often required to solve the problems and such measures could result in massive economic loss (loss cost) later on because of the additional work required in order to solve these problems. To find a solution to these problems, co-authors has changed its mindset from the conventional designing method that puts importance on hydraulic efficiency, and it is conducting studies on morphological design technology, in other words, optimization design technology in multiple regions (fluid, vibration, and structure) with highest priority on reliability in relation to rotating machinery.

The objective of this study is to apply a morphological design developed for a turbopump of aerospace rocket engine in Japan, into general industrial turbomachinery, and confirming the effect of this design method. In addition, it is particularly important to take into account the tradeoffs relationships between cost, vibration characteristic, and hydraulic performance in industrial world. Therefore, it is studied that the possibilities of new pump design that takes advantage of the multi-area optimization of morphological design.

For the purpose of improving the constructed design
process, it is confirmed that the advantages of a morphological design which uses the placement/layout of components (such as impellers and submerged bearings) as design parameters. In order to realize the obtained optimum design of a pump, robustness of an optimum pump design is studied finally.

### 2. Applicable Target Industrial Vertical Multistage Pump

One of the characteristics of morphological design is to handle the placement/layout of each component (such as impellers and bearings that configure a pump) as design parameters. Therefore, to use the advantage of this characteristic on the morphological design, it is appropriate to select a pump that allows the placement/layout of each component to be changed easily and clearly demonstrate the effect of an improvement caused by the changed placement/layout. Since the vertical multistage pump as shown in Figure 1 is a pump type that allows the placement/layout of pump components to be changed more easily than other pumps. Therefore, vertical multistage pump is selected as the objective of morphological design in this study. It is easy to consider changing the placement/layout of configuration components of a vertical multistage pump because of the following reasons: the entire shaft length is determined by the first stage impeller based on the operating conditions of the inlet suction pressure (Net Positive Suction Head or NPSH), the impellers can be placed as desired in order to secure the required head in the long shaft, and the submerged bearings can also be placed with a high degree of flexibility. As shown in Figure 1, the stationary components of a vertical multistage pump are consist of a suction bell, which is a suction side casing, a pump bowl, a discharge bowl, and a column pipe, which guides fluids flow from the pump stage to the discharge flange. A rotor consists of impellers and submerged bearings placed in the long shaft. In this study, a three-stage vertical multistage pump that is configured using three impellers and four submerged bearings is used.

### 3. Constructing Morphological Design Processes

The morphological design processes proposed by the co-authors consist of the two design process STEP-1 and STEP-2. In STEP-1, it is investigated that the placement/layout of turbopump components such as impellers, bearings, an inducer, and pump driving turbine. In STEP-2, it is designed the detailed shape of the rotor, such as bearing width, clearance and so on. Each step is a design process during which rotor
dynamic characteristics that indicate pump reliability are calculated and optimized. In this study, it was confirmed that the design parameters of the under-floor stationary part of this type of pump have high sensitivity for optimal design by a trial of the morphological design. Therefore, it is suggested that it would be constructive to carry out the design process in order to assure the vibration characteristics and rigidity of under-floor stationary part before making calculations in STEP-1 and STEP-2. For that reason, proposed design process in this study is included STEP-0 as a process to optimize the design of a column pipe. The proposed morphological design processes are shown in Figure 2. The optimized components in each STEP are also indicated in Figure 1.

The rotor dynamics analysis program used in this study is computer software that predicts the rotor dynamics of a vertical multistage pump (shown in Figure 1). This program has the following four features in comparison with a general rotor dynamics calculation program.

1) Analyzes the vibrations of a rotor and stationary part simultaneously.

2) Analyzes the vibrations of a vertical rotor.

3) Capable of studying and selecting the placement/layout of mechanical elements in STEP-1.

4) Performs an optimization calculation on the dimensions of each element in STEP-2.

Since the pump operating specifications are not changed for the morphological design in this study, the hydraulic design of existing impellers and the diffuser are used without changing them. Also, the features of morphological design processes include the design method that performs optimization in multiple regions using a combination of design parameters\(^{5}\). In other words, this method can performs the pump design used by optimizing rotor dynamics characteristics and saving cost at the same time, instead of the conventional design method that puts higher priority on hydraulic design. Therefore, it is necessary to determine the priority for each characteristic that have different evaluation scales. It is applied that the priority of calculating the importance based on a customer requirement using QFD method. The word QFD stands for “Quality Function Deployment” and this method starts from understanding a customer’s required quality and represents settings from the planning quality to design quality in a visual form\(^{5}\).

It is clearly quantified that the importance of the cost, vibration characteristic, and hydraulic performance, which are the evaluation function in terms of optimization in multiple regions (to be carried out in STEP-2), by use of QFD. In this way, the optimization can be made easier since optimization in multiple regions (STEP-2) can be converted into an optimization process for a single objective by ranking the importance of each characteristic.

In STEP-2, when the rotor dynamics calculation is performed, the cost evaluation and evaluation of the hydraulic performance of this pump are performed separately. Regarding the calculation of cost, the unit cost (proportionate to the volume) of a purchased part is calculated for the corresponding part whereas the material weight unit cost and manufacturing cost (labor cost) are calculated for a manufactured part. It is calculated the manufacturing cost of the parts whose characteristics (shape) change as a result of optimization based on the design parameters. It also

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**Fig. 2** Proposed morphological design process
compared the entire pump's total cost value with the total cost value of the present design (initial state of this pump). On the other hand, it is likely that a wearing clearance such as a casing ring impacts the hydraulic performance in addition to affecting rotor dynamics. Therefore, it is necessary to predict the changes in hydraulic performance and rotor dynamics calculation if the dimensions of these casing rings dimension change. In this study, with regard to the impact on hydraulic performance as a result of the selected design parameters, it took advantage of the fact that the hydraulic design of the pump does not change. In order to predict the leakage and disc friction loss that vary depending on each design parameter of STEP-2, the axial thrust prediction code Thrush® is used. Therefore, it is predicted that the changes in hydraulic performance using a simple one-dimensional calculation.

Finally, the rotor dynamics characteristics of minimum damping ratio, separation ratio which is the ratio between natural frequency and pump rotational frequency, and unbalance response are used as the objective functions for optimization in STEP-1 and the pump characteristics of cost, vibration characteristic, and hydraulic performance are used as the objective functions for optimization in STEP-2. The method of calculating the sum of each characteristic is the same as that provided in the paper.

4. Perform the Morphological Design Processes

The morphological design for the industrial multistage vertical pump in accordance with the morphological design processes already is carried out as shown in Figure 2.

4.1 Column pipe design optimization (STEP-0)

At first, STEP-0 for optimally designing the cross-sectional area of a column pipe is carried out. For STEP-0, it is necessary to consider the flexural rigidity and weight (≒cost) of an under-floor stationary components. As far as an industrial product is concerned, a lighter product is the better, and a product with higher flexural rigidity is more favorable if the weight is the same. Following this idea, favorable cases based on weight as the criteria among the under-floor stationary part shapes that satisfy the constrained condition of the separation ratio by changing the cross-sectional area (pipe diameter, pipe thickness, rib shape, and number of plates) of a column pipe within the range of material dimension specifications are selected as an input condition of a column pipe to be used for STEP-1.

The calculation results of STEP-0 are shown in Figure 3. The relationship between the weight of a column pipe and moment of inertia of area of the pipe
is shown in Figure 3. In addition, whether or not the separation ratio of under-floor stationary components of each case satisfies the constrained condition is also expressed in Figure 3.

The examples of typical cross-sectional areas of column pipes indicated by serial numbers (① to ⑤) are also shown in Figure 3. The present pump design ① is plotted using a symbol (□) on the Figure 3.

The present pump design does not satisfy the constrained condition and similarly many of the other pump designs showed in the peripheral area of the present design also do not satisfy the condition (●). Among the pumps that satisfy the constrained condition of the separation ratio (○), the one that has the lowest cost is the optimal design in STEP-0. As a result, column pipe design ② (Case 2) is the optimal design of STEP-0. Therefore, column pipe design ② is selected the input condition for STEP-1.

4.2 Optimization of the placement/layout of configuration components (STEP-1)

In this chapter, it is performed the optimization of the placement/layout in STEP-1. Therefore, it is treated that the design locations of the bearings (N pieces) and impellers (M pieces) as a problem in the calculation by setting the points for the placement locations of elements on a long shaft as a problem. Although the number of simulated cases increases, the calculation time required for each case is short, so calculations for all cases were carried out. In other words, STEP-1 was assured that the optimal design is obtained under the given conditions.

Regarding the objective functions, it was performed that the shaft vibration-related QFD, and obtained the following characteristics to be evaluated based on the result of the trial calculation subsequent to QFD: (1) separation ratio, (2) minimum system damping ratio, and (3) unbalance response. Therefore, it was scored that the calculation results for each rotor and under-floor stationary components using a weighted linear sum to get a single objective function.

Since the rotor dynamic characteristics are calculated in all combinations of the placement/layout in STEP-1, it is easy to study the characteristics of the best pump design. As a result, it is shown that the first-stage and second-stage impellers are located at the lower side of a pump and only the last-stage impeller is located at the upper side of the shaft in the optimum design of STEP-1.

It is confirmed that the most optimal design ultimately obtained in STEP-1 has been significantly improved in comparison with the present design of the vertical multistage pump. More specifically, the improvements of the optimal design obtained in STEP-1 are equivalent to 8.03 % in terms of damping ratio at the rotor, 2.82 % in terms of under-floor stationary part damping ratio, and 7.73 μmp-p in terms of the unbalance amplitude.

4.3 Optimization of the dimensions of pump components (STEP-2)

Optimization of the column pipe and placement/layout of configuration elements with respect to protection against the shaft vibration in STEP-0 and STEP-1 was already carried out. In STEP-2, it is carried out the optimization of the detailed design of pump components such as a casing ring. To achieve optimization, it is calculated a linear sum of the rate of changes in cost, vibration characteristic, and hydraulic performance as the objective functions and determined the priority of each characteristic by using the QFD method.

Figure 4 shows the result of optimization of each design parameter for the optimal placement/layout obtained in STEP-1 and it shows the cost, vibration characteristic, and hydraulic performance. Figure 4 shows the scores of vibration characteristic on their horizontal axes and cost reduction rate and the hydraulic performance (pump performance) change rate on their vertical axes. The black dot symbol (●) represents a standard design and standard configuration; the black triangle symbol (▲) represents the calculation result of Case 2 subsequent to completion of STEP-0 and STEP-1; the blank square box symbol (□) represents a design by aiming at the most highest score of vibration characteristic subsequent to the completion of STEP-0 and STEP-1; and the black square box symbol (■) represents the highest optimal pump design by aiming at the overall highest score. In Figure 4, the limit of cost reduction that can be achieved within the design parameter range calculated from a cost model is represented by a solid line and the limit of the predicted performance improvement calculated from
In order to clarify the improvement of the vibration characteristic in STEP-2, Figure 5 shows the minimum damping ratio, separation ratio and unbalance response. All axes of the figures are also made dimensionless by the present pump design values. The figure shows the calculation results of the rotor on their horizontal axes and those of the stationary components on their vertical axes. The most optimal pump design for the overall highest score is indicated by a black square box symbol (■). It is clearly confirmed that the optimal design has outstanding rotor dynamics characteristics since the separation ratio is sufficiently secured, the minimum system damping ratio of a rotor

If the design with higher priority on vibration characteristic (plotted by a blank square symbol (□) in Figure 4) is selected, the result shows an increase in cost and a slight decline in hydraulic performance.
is about 30%, the minimum system damping ratio of a stationary part is close to the upper limit, and the unbalance response is almost the minimum among all calculations.

In the case of the higher priority on the rotor dynamics characteristics that is plotted by a blank square symbol (□), the vibration characteristic scores are improved since the unbalance response is mostly more improved than the design optimized by the overall highest score (represented by a black square box symbol (■)).

4.4 Result of the morphological design
In order to clarify the results of the morphological design processes, Figure 6 shows 3D CAD models, which are the comparison result between the morphological design of a pump and the present pump design. The optimized pump design has the following features compared with the present pump design (optimized elements are underscored in Figure 6).

- Smaller diameter of the cross-sectional area of a column pipe and no ribs.
- The distance between the first-stage and second-stage impellers is farther and the location of the third-stage impeller is moved towards downstream side.
- The submerged bearings are placed as a pair with the impellers.

Comparing the optimized pump with the present pump, it is also clearly revealed from Figure 4 that the morphological design can improve the characteristics of cost, vibration characteristic, and hydraulic performance. It is concluded that the morphological design is very effective to the design method of pump.

5. Confirming the Usefulness of the Design Process and Improvement Effects of the Placement/layout
In this chapter, in order to confirm the usefulness of the morphological design processes and to clarify the improvement effects obtained in each STEP, intentionally performed the optimization calculation without following the sequence (STEP-0, -1, and -2) in the design processes.

Fig. 6 Comparison between the pump designs optimized by morphological design and the present pump design using 3D CAD models
as indicated in Figure 2 and compared with the optimal design.

Figure 7 shows the calculation result of each optimization design process, for the cost reduction rate vs. vibration characteristic as well as vibration characteristic vs. the hydraulic performance change rate, which are the objective functions.

In Figure 7, the black (filled) symbols are used to represent the column pipe cross-sectional area determined as optimal design among those studied in STEP-0 of Figure 2; the double symbols (e.g. double blank square box symbol or double blank triangle symbols) are used to represent one of the column pipe cross-sectional area that were not considered optimal design among the constrained conditions; and the blank symbols are used to represent the present design.

Also, the triangle symbols are used to represent the design results of STEP-0/STEP-1 and the square box symbols are used to represent the design results of STEP-2.

The alternate long and short dash line arrow is used to represent the improvement effects of STEP-0 and STEP-1, and the double-dashed line chain arrow is used to represent the improvement effects of STEP-2. Furthermore, the black dot symbol (●) represents the present design and the blank circle (○) represents the present design for which optimization was applied only in STEP-2.

Since the design parameters that affect hydraulic performance are not changed in STEP-0 and STEP-1 of Figure 7, figure shows that the improvements are made for cost reduction and vibration characteristic in STEP-0 and STEP-1. When the scores of vibration characteristic indicated on the horizontal axes are compared, the ranking of the optimal design subsequent to STEP-0 and STEP-1 are as follows: the optimal design of STEP-0 (black triangle symbol) > three designs other than the optimal design of STEP-0 (double triangle symbol) > present design (blank triangle symbol). The graphs show the same ranking for the scores of vibration characteristic for the square box symbols, which represent the results subsequent to STEP-2. Therefore, they indicate that the ranking of the higher-order designs does not change in the process from STEP-0/STEP-1 to STEP-2. It indicates that it is appropriate to proposed and carry out morphological design processes for a vertical multistage pump, which is the target of this study, in the sequence of STEP-0 and STEP-1 to STEP-2. Since the length of arrow lines are almost the same in each design step, it is concluded that the improvement effects in terms of overall values of each characteristic in STEP-0/STEP-1 and STEP-2 are at an almost equal level.

Generally, optimization of the pump design means optimization of dimensions in most cases. In the case of morphological design, however, the improvement of pump
design, especially the improvement of the rotor dynamic characteristics is achieved by means of the placement or layout of configuration elements in STEP-1. Therefore, it is showed that the improvement effects of placement/layout that affect shaft stability against vibration, based on Figure 7.

The improvement effects of placement/layout is clarified by the comparison of improvement results between a blank circle symbol (○), a blank triangle symbol (△) and a blank square box symbol (□). These symbols are represented as follows: A blank circle symbol (○): only optimization of the dimensions in STEP-2. A blank triangle symbol (△): only the optimization process is applied in STEP-1. A blank square box symbol (□): after optimization is applied in STEP-1 and -2. To be more clearly, the score of vibration characteristic of STEP-2 only (○) is 1.058, the score of vibration characteristic is 1.062 in STEP-1 only (△), and the score of vibration characteristic is 1.084 in both STEP-1 and -2 was applied (□). It is clearly shown that the improvement of the vibration characteristic in the only STEP-1 design is higher than that of the only STEP-2 design. Although this paper does not mention this improvement, it is confirmed that there is a high percentage of improvement in the unbalance response of a stationary components and the minimum system damping ratio of a rotor is also improved. In conclusion based on the above, the use of new design parameters, placement/layout, which are not included in the concept of conventional pump design (in addition to the use of dimensions), is more useful for improvement of rotor dynamic characteristics.

6. Investigating of Robustness by Applying the Optimal Design in the Viewpoint of the Production

As shown in Figure 6, when the actual manufacturing process of the optimal design is considered, there are always production variations in production tolerance and assembly tolerance. In this chapter, robustness of the optimal design and sensitivity of design parameters are analyzed by providing production variations (estimated for each design parameter). The word "robustness" in this paper is interpreted more broadly than the general meaning and defined as stability of the design within manufacturing errors in terms of the optimal design.

Figure 8 shows the relative values of cost reduction rate, the scores of vibration characteristic, and the hydraulic performance change rate by means of an L108 mixed level orthogonal array with three levels including the design values using manufacturing errors for optimal design parameters. The right side of Figure 8 shows the calculation results of the minimum system damping ratio and unbalance response of the rotor and stationary components among the scores of vibration characteristic. Each calculated characteristic value defined by a ratio relating to the present design and the variations for the optimal design are also indicated.

When each calculated characteristic value indicated on the left side of Figure 8 is examined, the variations for each optimal design after 108 times of calculations considering manufacturing errors, are extremely small where the scores of vibration characteristic is 0.2 %, cost reduction rate is 2.2 %, and hydraulic performance change rate is 0.6 % respectively. It is suggested that the optimal design obtained is comparatively robust design.

Furthermore, rotor dynamic characteristic variations range is from 1.6 % to 31.3 % that showed in the right side of Figure 8.

The variations for the scores of vibration characteristic, which is the overall value of the rotor dynamic characteristics, are extremely low (0.2 %). It is also confirmed that there is no drastic change in the vibration mode shape within the range of design parameter change.

As a result, it is concluded that the optimal design obtained in STEP-2 achieves high robustness even when manufacturing errors are taken into account. In order to clear the sensitivity for the design parameter of the optimal design, unbalance response as an example and analyzed its sensitivity as show in Figure 9. This sensitivity analysis result can clarify the important design parameters to be managed for manufacturing the optimal pump design.

Figure 9 shows a factor effect chart, which is the result of sensitivity analysis for the unbalance response to a rotor and stationary components. The double-headed
A Study of Morphological Design in an Industrial Vertical Multistage Pump

arrow in the figure indicates the design parameters that are in a tradeoff relationship. According to Figure 9, the sensitivity of the impeller weight enclosed in blue dashed line frame is highest for the unbalance response (this result is obvious because of the condition where the unbalance response amount is in proportion to the impeller weight). Following the impeller weight, the sensitivities of design parameters B, C, and D are also high. Therefore, even higher rotor dynamic characteristics (improved by the unbalance response) are achieved by reducing the impeller weight. The design parameters A, E, and F are in a tradeoff relationship pertaining to the unbalance response of a rotor and stationary components, which makes it necessary to take into account the manufacturing errors. Based on Figure 9, it is concluded that the impeller weight and unbalance response must be managed for manufacturing the pumps so that they fall within the range of production tolerance in order to achieve an optimal design.

Fig. 8  Robustness for manufacturing variations using the L108

Fig. 9  Sensitivity analysis result of design parameters for unbalance response when manufacturing variations are applied
7. Conclusion

In this paper, a morphological design is applied in to an industrial vertical multistage pump. It is also confirmed the effectiveness of the morphological design processes proposed by this study. The conclusions are summarized as follows:

(1) In the case of an industrial vertical multistage pump, the application of morphological design processes enabled us to design a new pump design that can be available with lower cost, higher hydraulic performance, and significantly higher vibration characteristic compared with present pump design.

(2) To confirm the usefulness of the design processes, it was compared with the optimums design processes and the design that were obtained by carrying out each process independently. As a result, it is confirmed that the morphological design processes proposed by this study is appropriate for an industrial vertical multistage pump.

(3) One of the features of morphological design processes is inclusion of a placement/layout of the configuration elements (such as impellers and submerged bearings) as design parameters. When the morphological design processes and design parameters of the placement/layout are applied, the improvement in terms of the rotor dynamic characteristics are high compared with the case where the placement/layout is not included as a design parameter. As a result, it is highly important to include the placement/layout design parameter.

(4) It is confirmed that the optimal design subsequent to STEP-2 is a stable pump design for a design parameter of production variations. As a result of a sensitivity analysis carried out on a design parameter of the optimal design for unbalance response, it is also confirmed that the impeller weight is extremely significant and its management from a manufacturing standpoint is very important.

This study enabled us to apply the knowledge of morphological design technology, e.g. originally researched and developed for a rocket turbopump, to an industrial vertical multistage pump. It was also able to conduct a case study of a new industrial pump that has an optimized design by considering multiple regions, cost, vibration characteristic, and hydraulic performance, which are in a tradeoff relationship. In the future, the morphological design processes improve even further; this design method will adapt the demands for higher reliability and higher performance and will be significantly useful for designing pumps that can be very competitive.

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