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Review Paper

Historical Perspective on Fluid Machinery Flow Optimization in an Industry

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Abstract

Fluid-dynamic design of fluid machinery had heavily relied on empiricism and experimental observations for many years. Since 1980s, thanks to the advancements in Computational Fluid Dynamics (CFD), a variety of flow physics have been revealed. The contribution by CFD is indispensable; however, the challenge is required not only on the advancements in CFD technologies but also innovation of “design (optimization) technologies” because of the complex interactions between 3-D flow fields and the complex 3-D flow passage configurations, etc. This paper presents historical perspective on fluid machinery flow optimization in an industry with some messages for the future.

Keywords: Design technology, Physical insight, Inverse design, Numerical optimization, Multi-objective, Adjoint

1. Introduction

Fluid machineries such as pumps, compressors, fans, and turbines are used in a variety of mechanical systems surrounding our life. Those used in infrastructures such as oil & gas production system, power stations, water supply/treatment system, and drainage stations are very crucial and must be robust and reliable to protect civil lives. Fluid machineries in other systems such as transport equipment, electrical equipment, and home appliances must be reliable to support comfortable living. All these mechanical systems also need to be efficient to reduce environmental impact. The Commission Regulation (EU) No 547/2012 of 25th June 2012 has drawn strong attention of the pump industries as it clarified Ecodesign (minimum efficiency) requirements for standard water pumps. It is easily envisaged that this kind of regulation will be the trend for all fluid machineries in not a distant future. Having these strong demands, the reliability and the efficiency of fluid machineries have been consistently improved through a variety of research and development activities in universities, research institutes as well as industries.

Ebara Corporation was established in 1912 with the desire to develop products according to the theory of centrifugal pumps of Prof. Ariya Inokuchi, Tokyo Imperial University [1]. However, the fluid-dynamic design improvements of pump flows had been heavily dependent on experiments, experience, and empiricism. In late 1980s, CFD (Computational Fluid Dynamics) based on RANS (Reynolds Averaged Navier Stokes) approximation using a simple turbulence model began to reveal the complex 3-D (three dimensional) flow physics in fluid machineries [2]. The fluid-dynamic design improvements of machine components were not very straightforward because of the complex three-dimensionality of flow fields (e.g. secondary flows), strong non-linearity between the flow phenomena and the complex 3-D flow passage configurations, etc. In 1990s, an innovative 3-D inverse design method was applied successfully for controlling complex secondary flows in pumps, compressors, and turbines and had achieved drastic improvements of their fluid-dynamic performances [3]. In 2000s, the inverse design method was coupled with CFD and optimizer to achieve automatic single objective numerical optimization [4]. More recently, multi-point/multi-objective optimization has been proposed employing, for example, DoE (Design of Experiments), RSM (Response Surface Model), and MOGA (Multi-Objective Genetic Algorithm) [5]. The challenge is continuing towards multi-disciplinary optimization having more objectives.

Digital engineering, including the use of numerical simulation and design optimization, is the key to responding above mentioned demands and achieving product innovation. This paper presents historical perspective on fluid machinery flow optimization in the author’s organization with some messages for the future.

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2. Design Technology

2.1 CFD vs. Design

The use of CFD for improving fluid machinery flows is indispensable. The advancements in computer performance (Flops) [6] as well as the CFD modeling are summarized in Fig.1. The computer speed increases by 10 times for every 3 to 4 years. This means that a CFD computation problem requiring 1 year computational time now could be done in a few days after several years. Such enormous advancements in CFD, however, are not directly connected to better designs because of the followings;

- CFD results do not tell directly about what sort of modification should be made to the flow passages
- three-dimensionality of flow fields is very strong and complex, dominated by secondary flow actions
- non-linear flow behavior of flows with respect to the flow passage configuration change
- flow passage configuration with free surfaces having difficulty to represent with simple formulation
- difficulty to keep design constraints while making arbitrary changes on flow passages

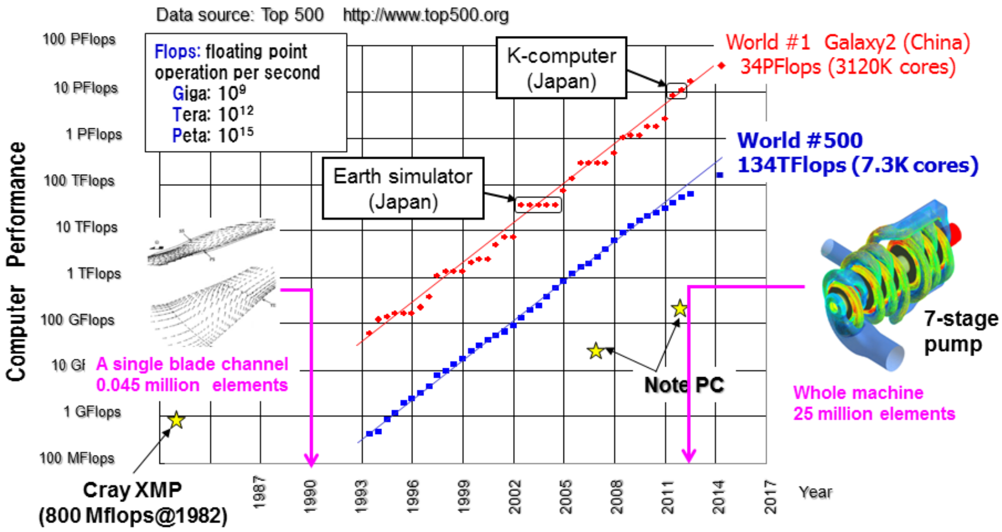


Fig. 1 Advancements in computer performance and CFD models

The ultimate goal of CFD is the replacement of experiments. However, performing detail experiments (perfect CFD) does not guarantee the design improvements. So, pursuit of the CFD accuracy is not sufficient for directly improving the design and it is clear that we need to make innovation in “design technologies” in addition to the innovation in simulation technologies.

2.2 Advancements in Simulation and Design Technologies

Figure 2 summarizes the history of advancements in simulation technologies as well as the design technologies at the author’s organization. Till 1970s, design improvements had been relied on experiments, designers’ experience, empiricism, and inviscid quasi-three dimensional (Q3D) steady flow analysis. In late 1980s, RANS CFD with simple turbulence model for one-pitch blade-to-blade flow was introduced [2]. In 1990s, 3-D inverse design method was introduced, and a variety of innovative designs had been done for pumps, compressors, and steam turbines [3, 7]. In 2000s, 3-D inverse design was coupled with the CFD and the numerical optimization [4], and this technology was expanded into a multi-objective optimization in 2010s [5]. The future will be the daily use of transient CFD with higher level of approximation and a multi-disciplinary optimization.

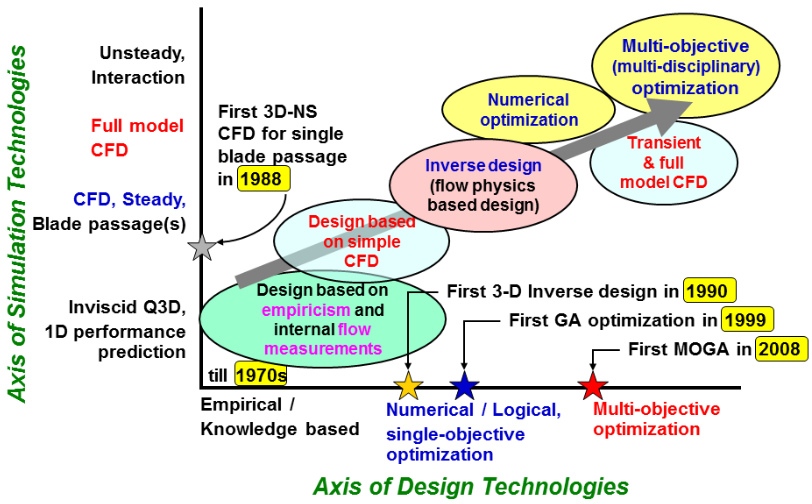


Fig. 2 History of simulation and design technologies at Ebara Corporation

Figure 3 presents the performance improvements during the last 30 years for a mixed-flow diffuser pump stage having the specific speed of about 800 (min^{-1}, m^3/min, m). The efficiency was normalized with the peak efficiency of 1970s design, and the head and the flow rate were normalized with those at the peak efficiency point for each design. The application of a steady state RANS based CFD code in 1990s brought large improvements in peak efficiency (+8.7 points) and the elimination of the stall phenomena at partial operating condition. Note here, the outer diameter of the bowl diffuser was increased by 24%. The peak efficiency improvements between 1990s and 2000s design was brought by the application of the potential flow based 3-D inverse design method, which will be described in detail later. The amount of the improvements in 2000s design is marginal (about 3 points compared to 1990s), but it should not be overlooked that 2000s design achieved more compact design compared to 1990s design by 15%. The important point to be noted here is the fact that the design improvements greatly rely on physical insight for improving flow fields and not necessarily the approximation level of the flow simulation used. This will be clearly demonstrated in the following section, where “potential flow” based inverse design achieved significant performance improvements.

People may feel improvement margin in peak efficiency is getting smaller and the huge investments in simulation and design technologies may not be justified. However, this is not true. If we are going to challenge against super compact design, one or two rank speed up of an electric motor, robust design to cope with highly distorted inflow, quick trade-off design satisfying complex demand of the customer, etc., the innovation in both simulation and design technologies is indispensable.

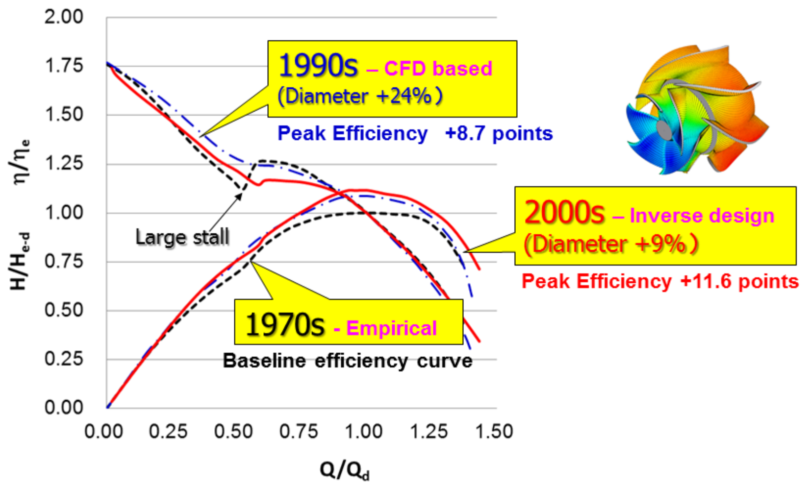


Fig. 3 Performance improvements of a mixed-flow pump stage during the last 30 years

3. Secondary Flow Control by 3-D Inverse Design Method

3.1 Impact of Secondary Flows

One of the most important phenomena in fluid machineries is the secondary flow motion. Figure 4 shows the secondary flow motions in a low specific speed diffuser pump stage (specific speed of 280 (min^{-1}, m^3/min, m)) visualized by a multi-color oil-film method using fluorescent powder as pigment having three different colors [8]. The blade suction surface (SS) was painted with yellow oil-film, the blade pressure surface (PS) with red oil-film, and the shroud and the hub surfaces with blue oil-film. After a few minutes operation at the design point, the flow pattern shown in Fig. 4 was generated.

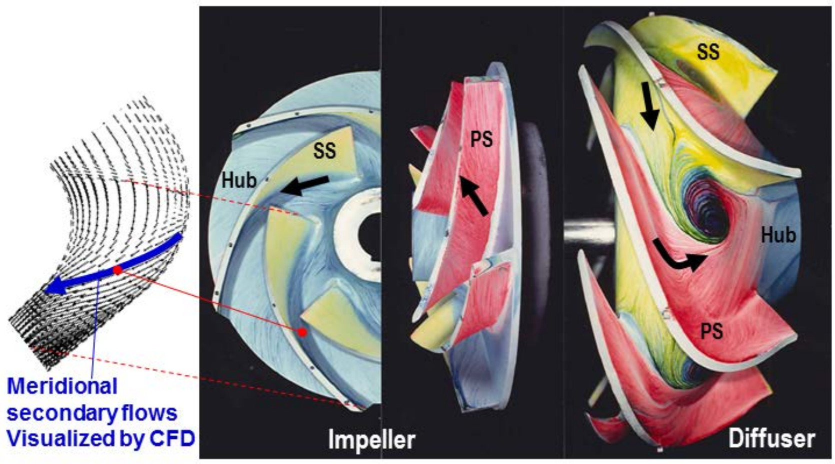


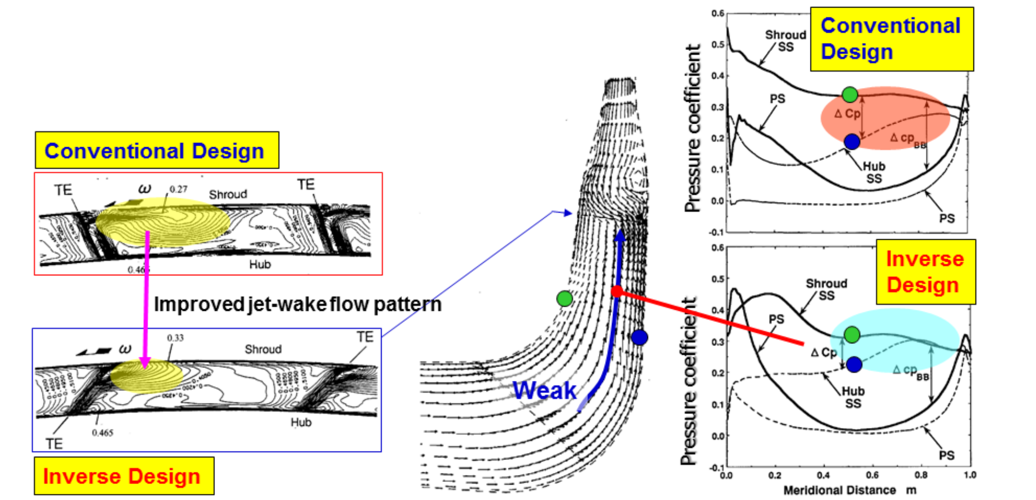
Fig. 4 Secondary flows visualized by multi-color oil-film method (conventional design pump)

Strong meridional secondary flows on the blade suction surface was visualized by blue stream lines covering yellow surface towards the blade exit, and also the strong meridional secondary flow on the blade pressure surface was visualized by red stream lines moving from the hub to the shroud surfaces. The pressure surface meridional secondary flows, after moving into the shroud surface, carry the low momentum fluid towards the blade suction-shroud surface corner. Due to these two strong meridional secondary flows, typical jet-wake flow pattern was established at the impeller exit (see Fig. 5(a)), which will generate high mixing losses and potentially has negative impact on the downstream diffuser performance. Inside the stationary bowl diffuser, the direction of the meridional secondary flows is opposite. The meridional secondary flows on the suction surface of the diffuser blade brought low momentum fluid in the viscous layers towards the hub surface in the fore part of the diffuser channel. The pressure surface meridional secondary flows, on the other hand, brought low momentum fluid towards the hub surface and then crossed the hub surface towards the blade suction-hub surface corner region in the after part of the diffuser channel. Because of these meridional secondary flow actions, the low momentum fluids accumulated along the hub-suction surface corner and separated due to the strong adverse pressure gradient in the same region, forming a massive separation vortex as clearly identified in Fig. 4, see Goto and Zangeneh [10] for more detail.

3.2 Secondary Flow Control by 3-D Inverse Design Method

Zangeneh [9] proposed a 3-D inverse design theory for designing mixed and radial flow fluid machines, where the blade configuration was obtained numerically for a prescribed blade loading distribution. As you may understand in relation with Figs. 4 and 5, the secondary flows are driven by the action of static pressure difference (reduced static pressure difference in rotating impeller case), while the inverse design derives the blade configuration for the prescribed blade loading distribution, i.e. the pressure difference between the blade pressure and suction surfaces. These two facts led to a physical insight that we should be able to control the meridional secondary flows by controlling the blade loading, which was confirmed by Goto et al. [3]. Based on this research, Zangeneh, Goto and Harada [7] had made challenge and succeeded in controlling meridional secondary flows systematically for the first time in the history of fluid machinery research.

As shown in Fig. 5(c), the meridional secondary flows on the blade suction surface will be suppressed by reducing the pressure difference ΔCp, which can be achieved by adopting fore-loading on the shroud side and the aft-loading on the hub side. The meridional secondary flows are significantly weak in Fig. 5(b) compared to the meridional secondary flow vectors in the left side figure in Fig. 4 for the conventional design. Due to the reduction of the meridional secondary flows, the jet-wake flow pattern was improved as shown in the relative velocity contours at the impeller exit, see Fig. 5(a).



(a) Exit relative velocity contours (b) Velocity vectors close to blade suction surface (c) Reduced static pressure distribution

Fig. 5 Impeller secondary flow control by 3-D inverse design method

In order to develop a pump series with suppressed secondary flows, similar approach had been taken for another specific speed pump impellers [11]. The guide line for suppressing meridional secondary flows for mixed-flow diffuser pump impellers was derived as shown in Fig. 6 [12]. Certain amount of the reduction rate of the reduced static pressure difference is required to suppress meridional secondary flows and its amount is larger for low specific speed pumps.

The diffuser blade was also re-designed by the 3-D inverse design method to suppress massive corner separation shown in Fig. 4. The flow physics of this massive corner separation is the accumulation of the high-loss fluids in the blade suction-hub surface corner and the excessive adverse pressure gradient in the same location. Based on this physical insight, the blade loading of the diffuser was optimized to avoid the accumulation of the high-loss fluids and mitigate the adverse pressure gradient [10]. The re-design by the 3-D inverse design method had succeeded in eliminating the corner separation, and the overall improvement of 5.3 points in pump stage efficiency was achieved.

The internal flows of a fluid-machinery are dominated by the secondary flow motion, and the secondary flows are driven by the pressure gradient on the flow passages. The static pressure field can be well predicted by a potential flow based theory, and this is why the secondary flows can be well controlled by the potential flow based 3-D inverse design method. So, the key for making efficient design innovation is not the high approximation level of the simulation technology but the physical insight and the use of suitable level of approximation.

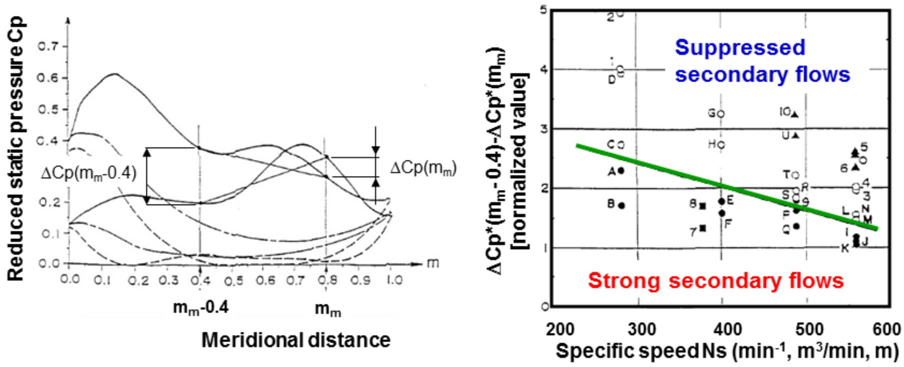


Fig. 6 Guide line to achieve suppressed meridional secondary flows

4. Numerical Optimization

4.1 Multi-Objective Optimization of Pump Characteristics

Customers/markets have a variety of demands, as shown in Fig. 7. Namely, in addition to the high peak efficiency at the design flow rate, low shut-off head is often specified in oil& gas industries to reduce the flange rating for lower piping costs. When electric motor costs are relatively high, low maximum power (often the shut-off power) is required to reduce overall machine costs. Non-stall head-flow performance characteristic curve is often critical to avoid any system instability at partial operating conditions. However, these customer demands are mostly in trade-off relationships each other, so the problem will become inevitably multi-objective optimization.

The multi-objective optimization was challenged [5] for a high-specific speed mixed-flow pump stage, having the specific speed of 1300 (min^{-1}, m^3/min, m), targeting the trade-off design of 4 objectives; namely, best efficiency, low shut-off head, stability in head-flow characteristics, and the low shut-off power. The methodology is the 3-D inverse design based multi-objective optimization. The Response Surface Model (RSM) was generated using the CFD results obtained for the design cases based on Design of Experiments (DOE). Then, MOGA (Multi-Objective Genetic Algorithm) was applied to the approximated function of the RSM to determine a set of optimal configurations (Pareto front). Note here, it is very important to adopt global exploratory optimization algorithm such as GA (Genetic Algorithm), because there are so many local optimum in the fluid-dynamic design optimizations.

The use of 3-D inverse design method, now commercially available [13], as a kind of shape generator is very effective from the following reasons;

- Complex blade profile can be generated by a small number of design inputs for blade loading.
- The design constraint on the design head is always guaranteed.
- The design inputs are flow physics based inputs (i.e. blade loading) and the resulting RSM is much smoother compared to the conventional approach using geometry related design inputs.

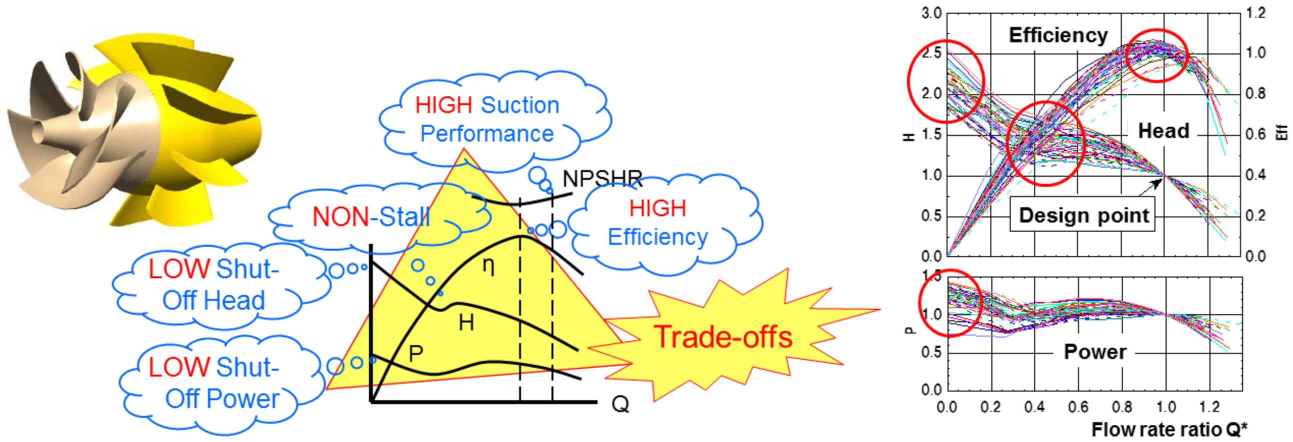


Fig. 7 Definition of multi-objective optimization

For each of the impeller and diffuser optimization process, 16 design cases were initially created by using L16 orthogonal table by setting the design parameters on 2 levels in the DoE. Then CFD calculations were performed for the 16 design cases for each of impeller and diffuser design, and the sensitivity analysis was made. Based on this, 6 design parameters having greater impacts on the target performances were selected, and then 45 design cases were created by setting the design parameters on 3 levels in the DoE. Then CFD calculations were performed for these 45 design cases and the prediction results were used to create the RSM. The performance curves of the 45 design cases predicted by CFD are presented in Fig. 7.

It can be easily understood that a variety of performance curves exist for the same design performance, which clearly shows the multi-objective trade-off nature of the problem. Finally, the MOGA was applied to the RSM without performing blade design and CFD computations.

If the target objectives are two, it is very straightforward to visualize the trade-off relationships (Pareto front) between two objectives. In the case of 3 objectives, it is still possible to visualize the Pareto surface in 3-D objective space, see Fig.8. Here, the black dots present all solutions and the blue dots present the Pareto surface on a projected 3-D space of objective functions. However, it is not easy to visualize the Pareto space if we have over four objectives.

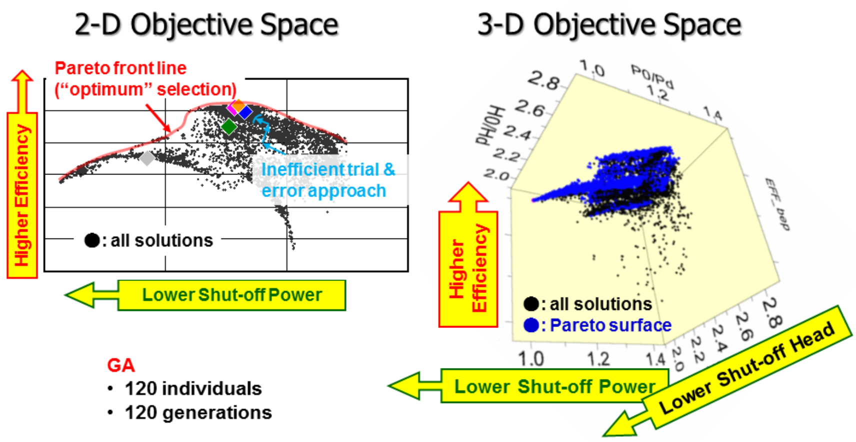


Fig. 8 Visualization of Pareto front on 2-D and 3-D objective space

The challenge to visualize multi-objective optimization having many design objectives had been made here using SOM (Self-Organizing Map) [14]. Figure 9 presents the SOM for each of the design objectives. The dots on each 2-D SOM present Pareto solutions, and the solution with higher characteristic value is shown with red color and lower value with blue color. The purpose of the optimization here is not to find a sweet spot solution for all objectives but to demonstrate good selection to meet a customer/market demand. For example, a plant may require low shut-off head pumps to reduce flange rating for saving piping costs while they may ready to accept some efficiency penalty (Design #1). A water supply system, on the other hand, may prioritize high efficiency and high stability while accepting high shut-off head and power (Design #2). So, 2-D SOM visualization/data mining method could be used effectively for offering the design most suitable for a specific customer/market demand. Since most of the design problems have a multi-objective trade-off nature, the real world problem cannot be handled efficiently without this kind of visualization/data mining method.

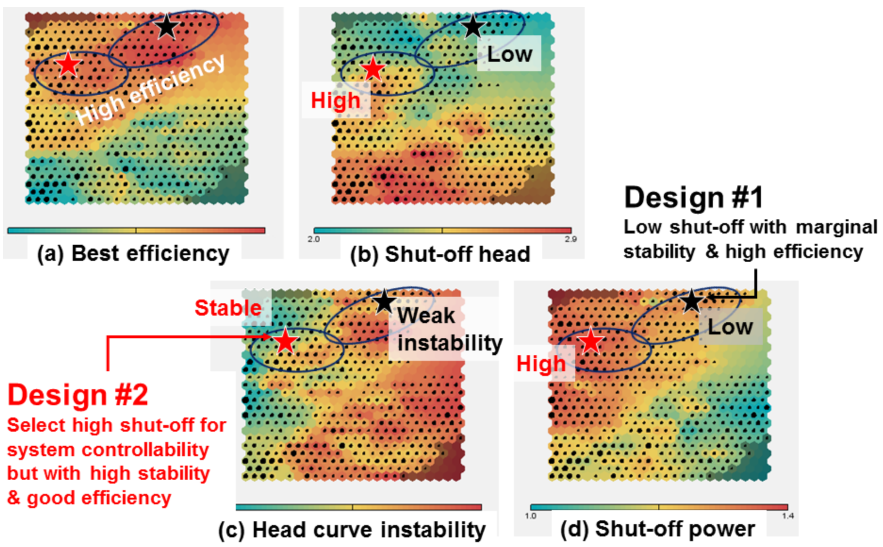


Fig. 9 Design selection using SOM (Self-Organizing Map) for 4 objectives

4.2 Optimization based on Simple Physical Model

Real world problem could be very complex. In theory, we could challenge such problems by numerical optimization combining multi-disciplinary simulation technologies, but in reality such approach will not be practical in foreseeable future. On the other hand, such a complex problem is often handled with simple empirical equations developed in the long history of design practice. Simple empirical equations, based on rich design experience, could be effectively used in numerical optimization.

Suction performance of a pump is the key characteristic to make drastic rotating speed increase, which has a big impact for reducing machine size and the required production costs. Numerical simulation of cavitation phenomena is still a challenging subject as there is no established cavitation model for predicting head breakdown at low NPSHa (Net Positive Suction Head available) accurately. On the contrary, it is well understood that the minimum pressure, the area of low pressure region on the blade surface, and the throat area of the blade-to-blade flow passage of the impeller have a close physical relationship with the suction performance of the pump. Also it is well known that the highest stress of the high speed impeller will appear around the root of the blade leading edge and it increases as the sweep angle of the blade leading edge increases. So, a multi-objective numerical optimization was carried out based on these simple empirical knowledge.

Figure 10 presents the results of numerical optimization using only 3-D inverse design method (without using CFD and FEM). The NPSHr (NPSH required: Empirical 1) corresponding to the minimum pressure is the measure of cavitation formation calculated using the pressure distribution obtained by the 3-D inverse design method. The sweep blade angle at the impeller inlet (Empirical 2) is the measure of the blade strength. Also the minimum throat area was imposed as one of the design constraints. Then 3-D inverse design was coupled with the MOGA and the Pareto front was obtained very quickly as is shown in Fig. 10. About 20,000 design cases were searched on a single core machine in about 39 hours. The effectiveness of this approach was confirmed by performing CFD/FEM for selected design cases on the Pareto front. In case we challenge the efficiency, the use of the guide line for suppressing secondary flow (Fig. 6) is very promising for performing optimization without using CFD. Similar approach could be effective for challenging complex problems such as fan noise control, cavitation erosion control, etc.

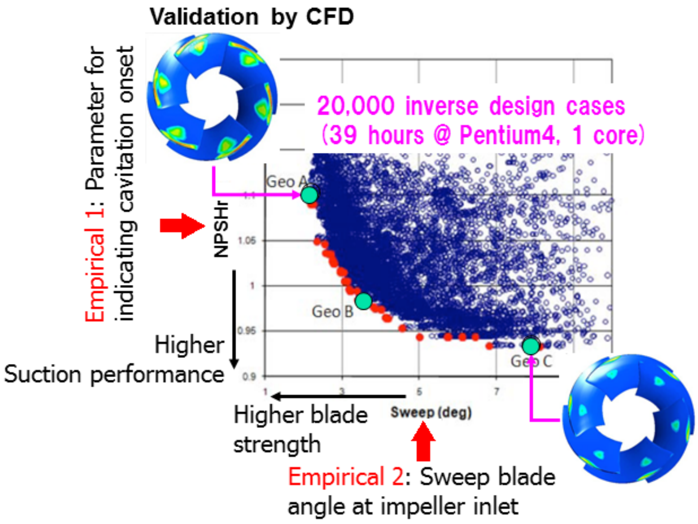


Fig. 10 Multi-objective optimization based on empirical objectives

4.3 Numerical Optimization of Complex Flow Passages

There is a complex 3-D configuration in fluid machinery, and it could be the key component for higher efficiency and/or larger performance stability of the machine. For example, the inlet channel has a big impact on the loss generation and the suction performance of the downstream impeller, and the outlet channel has an important role for the dynamic pressure recovery. Usually, these flow passages are modeled using 3-D CAD and numerical optimization of the flow passage is theoretically possible using parametric designs. However, due to the strong interaction between the flow fields and the flow passage configurations, in addition to the geometrical constraint, it is not straightforward to perform numerical optimization based on parameterized 3-D CAD model. The large number of control points to guarantee the flexibility of 3-D CAD geometry will require huge computational resources, and the design space is still very much limited.

TURBOdesign Shaper [15] uses any part of the computational mesh points as design variables, and the gradients of the flow equation in adjoint form are used to drive the existing shape to optimum, see Fig. 11. The computing costs are very cheap and independent from the number of design variables. The implementation of the geometrical constraints is also very straightforward.

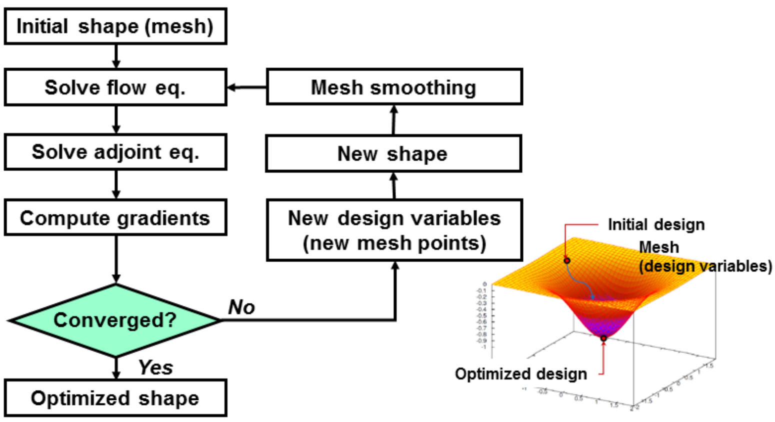
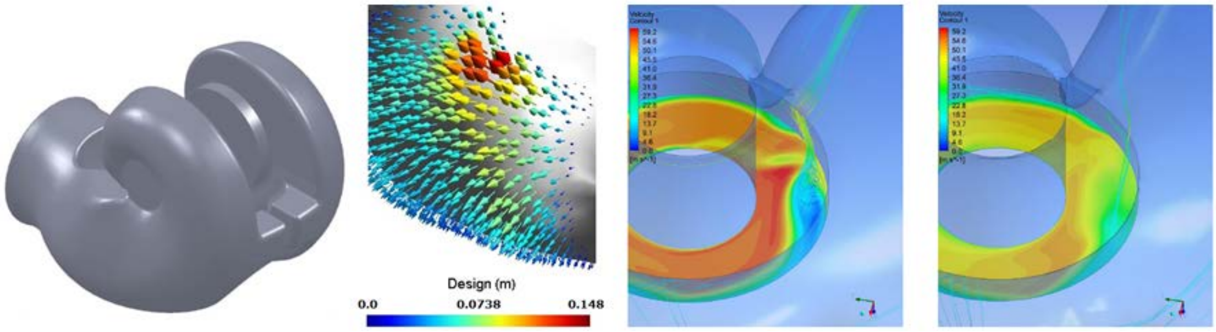


Fig. 11 Design approach based on adjoint

This approach was applied to an optimization of the suction chamber of a double suction pump, see Fig. 12(a). Figure 12(b) presents the sensitivity vectors obtained by solving adjoint equation and the suction chamber was modified in the direction of the vectors. Figure 12 (c) and (d) compares the CFD prediction of the velocity contours at the chamber outlet, i.e. the inlet to the impeller. In the original design, the local flow acceleration in the chamber formed a strong vortex and the resulting recirculation and non-uniformity. On the other hand, the optimized design has succeeded to suppress local acceleration and the resulting vortex formation. The optimized design contributed to reduce flow losses and improve impeller suction performance. Note here, this method is based on the "gradients" of the flow equation in adjoint form and the obtained solution could be the local optimum. However, the adjoint approach is still very effective as we will start from the best conventional configuration and also the sensitivity vectors such as Fig. 12(b) would give good physical insight for design improvement.



(a) Suction chamber model (b) Sensitivities (c) CFD for original design (d) CFD for optimized design

Fig. 12 Optimization of a double suction chamber for a centrifugal pump

5. Concluding Remarks

A variety of design technologies and their application were presented based on the author's experience. New experimental methods and advanced simulation technologies have been developed and applied to flow fields investigation. The ultimate goal of such research activities is to solve real world problems through the design process innovation and the resulting product innovation. Such problems are often very complex and multi-disciplinary, and it is still not practical to challenge such problems relying only on numerical optimization using advanced simulation technologies. So, the most important aspect in establishing effective design technology is to obtain a physical insight experimentally (using pressure probes, multi-color oil-film method, non-intrusive DPIV, etc.), numerically (using RANS, URANS, DES, LES, Adjoint, etc.), and/or empirically. Then the obtained physical insights would be combined with the prediction method of lower approximation level and implemented into multi-objective/multi-disciplinary optimization problems.

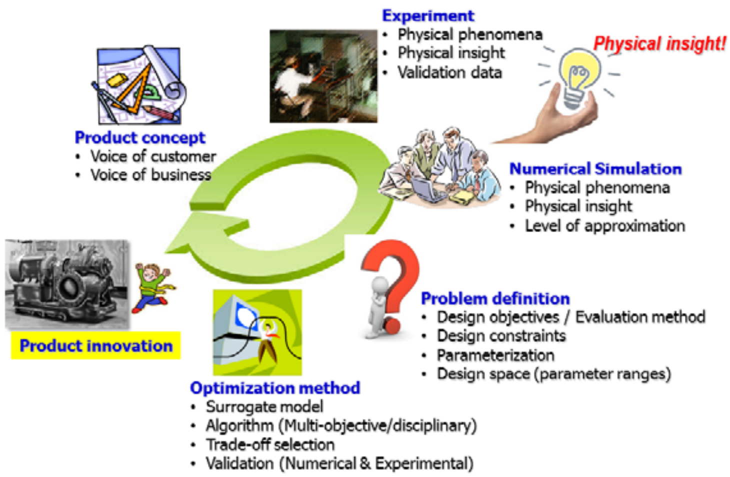


Fig. 13 Image of workflow for product innovation

Typical optimization process on the fluid machinery innovation is envisaged as follows, see Fig. 13;

1. Develop innovative product concept based on the voice of customers and the voice of business.
2. Design prototype and perform detail experiments and/or numerical simulations.
3. Perform data mining (including the use of sensitivity vectors obtained by adjoint approach) and obtain physical insights to affect/change/control the target phenomena.
4. Select lower approximation level prediction method (empirical equation, potential flow solver, RANS based CFD, etc.).
5. Set-up optimization problem and define design space (shape deformation using 3-D inverse design, parameterized 3-D CAD, etc. with minimum design variables and suitable design range).

6. Perform multi-objective/multi-disciplinary optimization, preferably using global exploratory optimization algorithm.
7. Visualize objective space obtained (projection to lower dimension, use of self-organizing map, etc.).
8. Make trade-off design selection and validation (numerically and/or experimentally).

The value of numerical optimization is threefold; 1) pursue ultimate performance improvements in a specified design space, 2) support innovative product development challenge involving multi-objective and multi-disciplinary design aspects, and 3) perform physics based design optimization for controlling flow phenomena and systematize design knowledge, which possibly comprehends empirical design practice/know-how. Note here, the design technology innovation should advance hand-in-hand with manufacturing technology innovation. This is because numerically optimized shape can be very complex and difficult to manufacture accurately by conventional manufacturing technologies, and innovative manufacturing technology, such as 3-D printers, will expand design space and bring new possibility in product innovation.

In conclusion, in addition to the development of the next generation simulation technologies, advancements in the design technology are the key for success in product and process innovation. Inverse design based numerical optimization, with implementation of physical insight, is effective to efficiently solve multi-objective and multi-disciplinary real world problems. Visualization of multi-dimensional objective space is also important to make efficient trade-off design selection. Continuous challenges are envisaged in product innovation and work process innovation, employing numerical optimization, especially by young generations familiar with the digital engineering.

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Nomenclature

Cp	Pressure coefficient
H	Head
m	Normalized meridional distance
$NPSHr$	Required net positive suction head
P	Power
Q	Flow rate
Q^*	Normalized flow rate Q/Q_d
ΔCp	Difference between Cp at shroud and hub on SS
ΔCp^*	Normalized pressure coefficient difference
η	Efficiency
<u>*Subscript*</u>	
0	Shut-off condition
d	Design point
e	Baseline
m	Location of minimum ΔCp

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