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Review

Design Optimization of Hydraulic Machinery Based on ISIGHT Software: A Review of Methods and Applications

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Abstract: Optimizing hydraulic machinery is a critical research area within the field of fluid mechanics, aiming to enhance product design efficiency and improve performance while reducing development time. The application of intelligent algorithms and combinatorial optimization strategies has become increasingly prevalent in this domain, providing a comprehensive understanding of optimization-related theoretical developments. Recently, the emergence of ISIGHT software as a new technology for software integration platforms has opened new avenues for optimization in hydraulic machinery. By leveraging intelligent algorithms and combinatorial optimization strategies, ISIGHT software provides a comprehensive framework for optimizing hydraulic machinery. This paper serves as an introduction to ISIGHT software, highlighting its advantages in addressing optimization problems. It presents a detailed examination of the process and technology involved in hydraulic machinery optimization based on ISIGHT software, along with its practical application. Furthermore, the paper summarizes the future development trends of ISIGHT software, offering engineers a theoretical foundation and reference for optimizing hydraulic machinery performance. Overall, this paper provides a valuable contribution to the field of hydraulic machinery optimization, showcasing the potential of ISIGHT software.

Keywords: hydraulic machinery; design optimization; optimization algorithms; ISIGHT software

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1. Introduction

The discipline of hydraulic machinery encompasses diverse areas and is closely linked to sustainable energy and ecological development, offering significant socioeconomic benefits. Optimal design plays a crucial role in achieving high-quality industrial products. With the advancement of hydraulic machinery technology, optimizing hydraulic machinery performance has emerged as a key research focus. In China, research on the multi-parameter multi-objective optimization design method of hydraulic machinery has become a prominent area of investigation [1].

ISIGHT software has gained widespread use in hydraulic machinery optimization, offering several advantages over traditional approaches. It efficiently solves complex optimization problems, expediting the process through user-friendly operation, multilevel parallel computing, and intelligent optimization [2]. Researchers can effectively leverage ISIGHT software for optimal design, enabling them to achieve their design goals and enhance hydro-mechanical performance.

2. Hydro-Mechanical Design Optimization

Hydraulic machinery employs liquid as a working medium to convert mechanical energy and transfer energy between fluids with varying energy levels. It is a widely used piece of mechanical equipment classified into prime movers and working machines based on the direction of energy transfer. Additionally, hydraulic machinery can be categorized as a vane type or displacement type depending on fluid and mechanical interaction.

In industrial production, hydraulic machinery plays a significant role, with common types including hydraulic turbines, pumps, submersible mixers, and marine propellers [3]. Figure 1 illustrates commonly used hydraulic machinery. A turbine converts the energy of water flow into rotational mechanical energy to drive a piston or tie rod. Pumps, on the other hand, enable the conversion of mechanical energy into the kinetic, potential, and internal energy of the fluid. A submersible mixer transforms mechanical energy into fluid energy to create water flow and achieve the mixing function. Lastly, a marine propeller converts the mechanical energy of engine rotation into kinetic energy, propelling the boat forward.

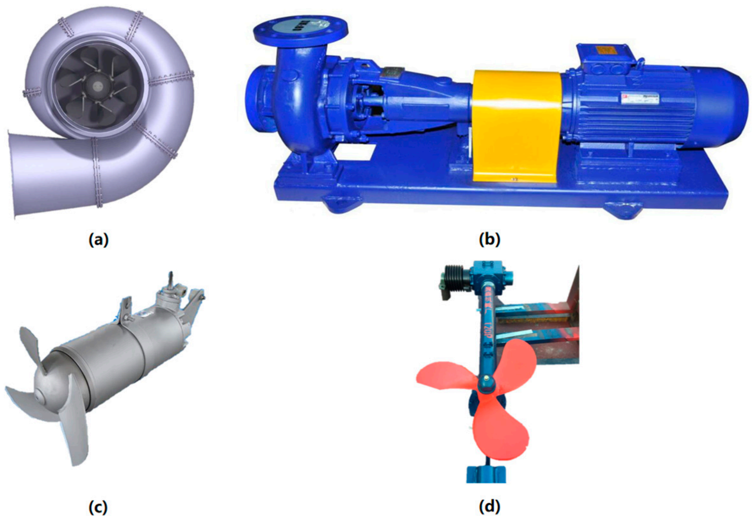


Figure 1. Commonly used hydraulic machinery: (**a**) axial rotating paddle turbine; (**b**) centrifugal pump; (**c**) submersible mixer; (**d**) marine propeller.

Hydraulic machinery design optimization encompasses various aspects, such as flow channel design, impeller design, and structural design. The flow channel, which is the most critical component of hydraulic machinery, can be optimized to reduce water resistance and eddy losses, thereby enhancing water energy conversion efficiency. The impeller, as the core component, is pivotal in determining the efficiency and output power of water energy conversion. Improving the flow coefficient and impeller efficiency through impeller design optimization can lead to enhanced hydraulic machinery efficiency. Furthermore, the structural design of hydraulic machinery, including bearings, seals, supports, and others, directly impacts the stability and reliability of hydraulic machinery. Optimizing the structural design can improve the stability and reliability of hydraulic machinery. In summary, optimizing hydraulic machinery design involves the comprehensive consideration of multiple aspects and continuous exploration and innovation to enhance hydraulic machinery efficiency and economic benefits.

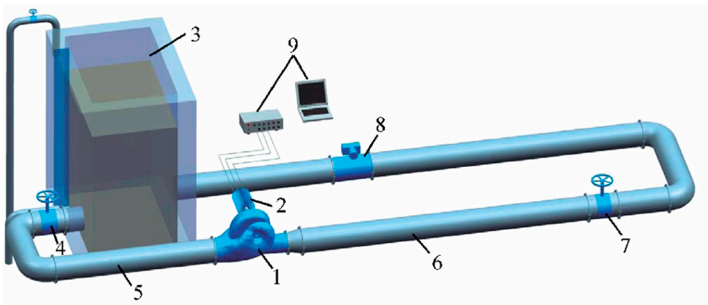
Hydraulic machinery possesses immense potential for enhancing energy efficiency and reducing reliance on non-renewable energy sources such as oil and coal. Renewable energy sources, particularly water energy with minimal environmental impact, offer a promising pathway for sustainable energy development. Widely applicable across water engineering, industry, biomedical engineering, the power industry, and aerospace technology, hydraulic machinery optimization plays a crucial role in China's pursuit of sustainable and scientific development objectives.

3. Traditional Optimization Methods

Optimal design is the development direction of engineering design. The traditional methods for optimizing hydraulic machinery mainly include the experimental method, empirical formula method, and model test method.

3.1. Experimental Method

Experiments are essential for investigating internal flow problems in hydraulic machinery. The experimental method involves conducting tests on hydraulic machinery, measuring various parameters, and subsequently analyzing the data to determine the best operating parameters. The structure depicted in Figure 2 is a comprehensive pump test bench, which consists of a water pump, a motor, inlet and outlet pipes, a gate valve, a circulating water tank, and testing equipment. The vibration is measured by a vibration acceleration sensor positioned on the bearing seat at the pump drive end, and the flow is measured by an electromagnetic flow meter on the outlet pipe. The reliability and objectivity of experimental results are valuable for validating theoretical solutions.



1-Experimental Pumps; 2-Electric Motors; 3-Circulating Water Tank;
4-Inlet Gate Valve; 5-Water Inlet Pipe; 6-Water Outlet Pipe;
7-Outlet Gate Valve; 8-Electromagnetic Flow Meter; 9-Vibration Collection System.

Figure 2. A comprehensive pump test bench.

In the early stages of hydraulic machinery design, experiments play a crucial role in finalizing the design. However, experiments face several challenges that are difficult to overcome. The complexity of hydraulic machinery structures makes experiments costly, time consuming, and labor intensive. Additionally, external factors such as measurement methods and instruments further impede the attainment of complete accuracy in experiments [4].

3.2. Empirical Formula Method

The empirical formula method establishes mathematical formulas based on experimental data and empirical knowledge to compute the performance parameters of hydraulic machinery, such as power output, efficiency, and flow rate. These formulas are refined and validated through practical applications and experiments.

However, this approach had limitations, including the need for extensive experimental data and empirical knowledge, as well as the lack of a systematic method for optimizing hydraulic machinery design.

3.3. Model Test Method

The model testing method involves constructing a small physical model of the hydraulic machinery and conducting laboratory tests. These tests provide data on hydromechanical properties such as water velocity, pressure, flow, and vortices. The obtained data are used to evaluate the model's performance and identify areas for improvement. Design optimization can be guided by these data to enhance the performance and efficiency of the hydraulic machinery. However, the model testing method requires specialized equipment and technical support, resulting in high costs and time consumption.

Each traditional optimization design method has specific application scenarios and limitations and should be selected and applied according to the specific problem at hand. One limitation of traditional optimization design methods is their heavy reliance on empirical knowledge, which hampers the acquisition of theoretically optimal design solutions.

4. Modern Optimization Methods

Modern computer technology, utilizing numerical simulations and optimization algorithms, has surpassed traditional optimization design methods. Computational fluid dynamics software enables researchers to quickly assess the performance and internal flow field distribution of hydraulic machinery.

4.1. Numerical Simulation Methods

Numerical simulation methods have emerged with the development of computers and computational techniques. Common calculation modes in hydraulic simulations include the direct numerical simulation model, large eddy simulation model, and Reynolds-Averaged Navier–Stokes model. Numerical calculation methods encompass the complex function method, finite difference method, finite volume method, finite element method, finite analysis method, and boundary element method. The appropriate selection of calculation mode and numerical calculation method depends on the specific hydraulic problem.

Previously, the design of airfoils or impeller grilles in hydraulic machinery was mainly carried out through experimental methods. However, since the 1950s, with the development of computational fluid dynamics, people have begun to use flow calculations combined with empirical corrections to optimize design methods. In recent years, with the rapid development of computer technology, the optimization design of hydraulic machinery has been improved from the optimization of a single impeller to the runner and even all of the flow through components [5].

For example, Song et al. used a numerical simulation method to study the flow field characteristics inside a reversible unit under hydraulic turbine and water pump working conditions. The results show that efficiency improved when using a 6 long 6 short, 7 long 7 short, and 8 long 8 short blade wheel in water turbine conditions. In pump conditions, the 6 long 6 short and 8 long 8 short blade wheels decreased in efficiency, while the 7 long 7 short blade wheel improved efficiency [6]. Wang et al. optimized a fixed guide vane through numerical simulation and found that the modified diffuser cross-sectional area increased and the nose area conformed better to a streamline shape. The improved guide vane had better symmetry, and the velocity flowed out in an axisymmetric and equispeed manner, reducing internal interference and machine vibration [7]. Lei et al. analyzed the instantaneous flow velocity of the blade cloud pressure, water guide mechanism, and internal flow passage of the water turbine under typical conditions through numerical simulation. The results show that simultaneous transformation of the turbine and water guide mechanism improved the hydraulic characteristics of the mixed flow water turbine overcurrent component, improved efficiency and anti-cavitation performance, increased output, enhanced operational stability, and reduced transformation costs [8].

In the field of submersible mixers, numerical simulation has been utilized to optimize the mixer arrangement and investigate flow field distribution in various scenarios. Chen et al. used numerical simulation to optimize the arrangement of the mixer using clear water as the study medium and found that the mixer arrangement near the inlet increases the area of the central low-velocity region [9]. Xu et al. studied the flow field distribution in a pool under two cases of submersible agitator installation depths of 3 m and 5.72 m using clear water as the medium and found that the submersible agitator installed near the bottom of the pool formed a high-speed flow zone on the surface of the pool bottom. This jet will flush the bottom of the pool, prevent solid particles from being deposited on the bottom, and homogenize the media in the pool [10]. Similarly, Zhang et al. used numerical simulation with clear water as the medium to investigate the velocity distribution of the flow field in the mixing tank under different horizontal installation angles of 30°, 45°, 60°, and 90° and found that the different installation angles had a significant influence on the flow field, with the best results obtained at an installation angle of 45° [11].

4.2. Design of Experiment Optimization

The design of experiments plays a crucial role in the development of hydraulic machinery. This method is a powerful means of dealing with multi-factor combinations by ensuring the uniformity of distribution of optimal design solutions in the design space, with fewer tests, shorter test cycles, lower costs, and quicker acquisition of accurate conclusions and a better number of test results. Different designs of experimental schemes should be selected based on the study's purposes, with full factorial tests, partial factorial tests, orthogonal tests, and Latin hypercube design robustness tests being commonly used methods [12].

Early scholars used the design of an experiment to determine the influence of different turbine and pump geometric parameters on hydraulic performance parameters, which provided essential references for hydraulic machinery design and improved the relevance of design variable selection. Building on this foundation, many researchers have employed the experimental method to optimize the design of various types of pumps. Currently, the orthogonal design method is the most widely used design of the experimental method.

For example, Zhang et al. employed the orthogonal test method to optimize the primary parameters of the impeller, resulting in improved hydraulic efficiency and increased impeller efficiency in a centrifugal pump [13]. Wang et al. developed an optimization mathematical model using orthogonal tests to enhance cavitation resistance and reduce the cavitation margin and steam mass fraction in a centrifugal pump [14]. Zheng et al. optimized the number of vanes, the hub ratio, the airfoil shape, and the distance between the guide vanes in an axial flow pump using the orthogonal test method, resulting in increased efficiency, decreased shaft power, and a reduced pressure pulsation coefficient [15]. Furthermore, Yuan et al. optimized the matching of an axial flow pump impeller and guide vane based on the orthogonal design of the experimental method, resulting in a significant improvement in the weighted average efficiency, particularly at high flow rates, while maintaining the design head [16].

4.3. Intelligent Algorithm Optimization

Optimization methods based on the design of experiments offer the advantage of a straightforward design process, but the resulting optimal solution may not be the global optimal solution in the design space. Intelligent algorithms possess superior global search capabilities, making it easier to obtain global optimal solutions compared to the design of experiment-based methods. Commonly used intelligent algorithms include gradient algorithms, genetic algorithms, and particle swarm algorithms [17].

Zhang et al. applied a particle swarm intelligence algorithm to optimize the design of a hydraulic turbine airfoil, resulting in improvements in the pressure coefficient, lift-to-drag ratio, cavitation priming, and full cavitation performance [18]. Yang et al. used a new particle swarm algorithm based on particle generators to optimize airfoil shapes, which showed high accuracy according to the numerical results [19]. Iwase et al. optimized the design of forward-curved fan blades using simulated annealing algorithms, achieving lower shaft power than the initial design, particularly at low flow rates [20].

With the emergence of increasingly complex and large-scale hydraulic machinery optimization design problems, researchers soon found a new optimization path using the genetic algorithm for multi-objective optimization problems. Hu employed a genetic algorithm to optimize the design of a centrifugal pump impeller, successfully improving hydraulic performance under working conditions [21]. Tan et al. established a multi-objective optimization model using a genetic algorithm to develop horizontal axis tidal turbine design software, resulting in a better blade airfoil family with improved hydrodynamic characteristics [22]. Guo et al. developed an automatic optimization method for centrifugal pump impeller modeling using an improved genetic algorithm operation, significantly enhancing the hydraulic performance of both pumps under design conditions [23].

In conclusion, intelligent algorithms, particularly genetic algorithms, have a wide range of applications in hydraulic machinery optimization. Genetic algorithms offer good global space-seeking ability and can effectively solve multi-objective optimization problems. More and more researchers have combined genetic algorithms into optimization research, and all have achieved good results.

4.4. Combinatorial Optimization Strategies

Combining experimental design, approximate models, and intelligent algorithms, the combinatorial optimization strategy is an effective approach to conserve computational resources. This strategy begins by constructing a sample space through experimental design and establishes a functional relationship between design variables and optimization objectives using approximate models such as response surface methodology, Kriging models, radial basis neural network models, and artificial neural networks [24].

In the field of hydraulic machinery optimization, researchers have widely adopted the combinatorial optimization strategy. For instance, Zhao et al. employed the NLPQL algorithm to optimize the parameters of a high-ratio rpm centrifugal pump, leading to improved actual efficiency and head under rated flow conditions compared to the original model [25]. Similarly, Derakhshan et al. utilized an artificial neural network and artificial bee colony algorithm for centrifugal pump impeller optimization, effectively enhancing the hydraulic efficiency of the pump [26]. Wang et al. proposed an approach based on the Kriging approximation model and genetic algorithm for a waste heat discharge pump. The optimized impeller exhibited a more uniform relative velocity distribution and reduced hydraulic loss [27]. Heo et al. utilized an approximate model and a sequential quadratic programming algorithm to optimize the design of a centrifugal pump by establishing a functional relationship between impeller geometry parameters and hydraulic efficiency. The optimization resulted in improved hydraulic performance [28]. Yuan et al. combined numerical simulation, the design of experiments, approximate models, and genetic algorithms to obtain the optimal combination of centrifugal pump impeller parameters. The optimized pump demonstrated increased hydraulic efficiency, improved internal flow, and a reduced vortex region compared to the original design, leading to enhanced operating stability [29]. Furthermore, Pei et al. employed an artificial neural network to optimize the design of the elbow-shaped inlet channel of a pipeline pump, leading to improved hydraulic efficiency under design working conditions [30]. Xu et al. optimized the impeller blade shape design of mixed flow pumps using radial-based neural networks, resulting in a more uniform velocity distribution in the pump under multiple operating conditions [31]. Wang et al. utilized a radial-based neural network and genetic algorithm to optimize the design of a mixed flow pump impeller, achieving enhanced hydraulic characteristics and performance for a high-specific-speed mixed flow pump [32].

In the field of marine propeller design, Wang et al. developed a propeller optimization method. Their approach employed a neural network approximation model along with the design of the experimental method, elliptical basis function neural network approximation models, and genetic algorithms. This optimization technique successfully reduced the propeller torque coefficient and improved propeller efficiency [33].

Modern optimization methods require substantial computational resources and data support. However, they offer advantages such as low cost, high efficiency, and good reproducibility compared to traditional test methods.

5. Optimization of Hydraulic Machinery Performance Using ISIGHT Software

5.1. Introduction to ISIGHT Software

ISIGHT software was initially proposed by Dr. Tong in the 1980s, encompassing mathematical tools, optimization-seeking approximation techniques, and design exploration techniques. Widely employed in numerous fields such as the automotive, power, aviation, aerospace, electronics, marine, and weaponry fields, ISIGHT stands as one of the most extensively used commercial multidisciplinary optimization softwares [34].

ISIGHT itself does not function as an optimization solver and holds no direct association with optimization objectives and variables. However, it possesses the capability to be programmed to interact with other software, such as UG, Fluent, ANSYS, and others, facilitating numerical simulations. Consequently, ISIGHT primarily assumes the role of a "software integration platform," integrating the relevant simulation software to establish a comprehensive optimization process, with the initial values of variables, constraints, and objective functions set accordingly. For example, Wang integrated Pro/E, Gambit, and Fluent software into ISIGHT and developed a fully automated optimization method for centrifugal pump shaft surface projection diagrams based on CFD calculations. The optimized head increased by 4.85%, and the hydraulic efficiency increased by 1.31% [35]. Shi et al. established an automatic optimization design platform for axial flow pump vanes based on ISIGHT software, which significantly improved the hydraulic performance of the vanes after optimization [36].

Incorporating 3D modeling software, meshing software, and simulation software, ISIGHT streamlines the optimization process by organizing and simplifying it within a unified framework. By automating the optimization cycle through calculation software, ISIGHT effectively addresses the drawbacks of the traditional design process and realizes the efficient and automated optimization tasks demanded by modern industrialization.

The operation of ISIGHT software relies on integrating the user's desired modeling software or self-programmed solutions through the process integration module. The problem definition module allows for the establishment of selected design variables, constraints, and objective functions for the entire optimization design task. Subsequently, the optimization design cycle steps are automatically executed, with the embedded solution monitor module enabling real-time monitoring of variable values and target value changes. If any deviations or excesses of reasonable ranges are detected before obtaining the optimal solution of the Pareto front, the calculation can be promptly halted to prevent wasteful resource expenditure resulting from inaccurate calculations. These operations are effectively coordinated by the task management module. The architecture of the main ISIGHT module is shown in Figure 3.

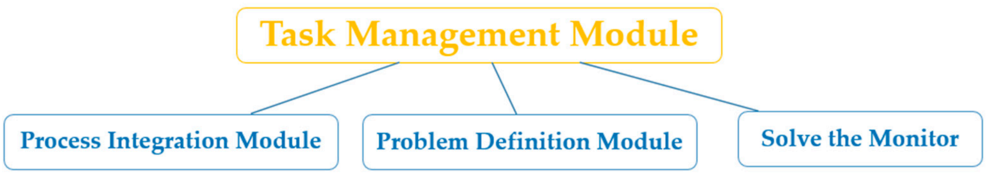


Figure 3. ISIGHT main module architecture.

5.2. Main Advantages of ISIGHT Software

(1) Integrated simulation process

ISIGHT is a system optimization and integration software based on multiple software programs working together, enabling the integration of hundreds of software programs in different disciplines, such as mechanics, electricity, and engineering, under its built-in software platform.

(2) Parametric research and design optimization

ISIGHT offers built-in optimizers, the design of experiments, approximate models, and many other design exploration tools. It provides various algorithms, such as the design of experiments, optimization algorithms, approximate models, Monte Carlo analysis, Taguchi robustness design, 6Sigma quality design methods, and others. These algorithms can be combined to form a comprehensive optimization strategy based on the characteristics of the optimization problem.

(3) Data visualization

ISIGHT software also provides powerful graph generation tools that can be used to visualize the effects of optimization on hydro-mechanical systems. Various graphs, such as bar charts and line graphs, can be generated to show system parameters and the relationships between them. These graphs can be used to quickly identify system bottlenecks and areas where optimization could be beneficial. Additionally, real-time data can be displayed on the same graph to illustrate the effects of optimization and how various variables interact with each other.

(4) Data analysis

ISIGHT provides various data analysis tools. Optimization analysis reports are automatically generated, and the best solution can be found efficiently through statistical analysis and the visual display of optimal results.

(5) Openness and scalability

ISIGHT has excellent openness and can be extended with functions as needed, including interface customization and algorithm embedding [37].

5.3. ISIGHT Software: Empowering Optimal Design in Hydraulic Machinery

The utilization of ISIGHT software has emerged as a powerful tool for implementing both single-factor and multi-parameter optimization approaches in hydraulic machinery design. This software facilitates the construction of mathematical models that effectively consider the interactions among multiple factors. By employing advanced optimization algorithms, ISIGHT enables designers to identify optimal solutions for their designs. One notable strength of ISIGHT software lies in its ability to support multi-objective optimization. This capability is crucial in achieving a balanced optimization state, where the enhancement of one objective does not compromise the performance of other objective functions. By harnessing the capabilities of ISIGHT software, hydraulic machinery designers can achieve more comprehensive and efficient designs that lead to better overall performance [2].

Initially, in hydraulic machinery design, the straightforward approach of single-factor analysis is employed. This approach involves selectively altering a single factor, such as the number of blades, blade curvature angle, or guide vane angle, to observe its impact on machinery performance. Although this method is simple to implement and provides quick insights into the influence of individual factors, it fails to consider the intricate interactions that may arise among multiple factors.

In contrast, the multi-parameter optimization method entails constructing a mathematical model that accounts for the combined effects of multiple factors on hydraulic machinery performance. By utilizing optimization algorithms, this approach seeks to identify the optimal design solution. Unlike single-factor analysis, the multi-parameter optimization method comprehensively considers the interactions among various factors and yields more holistic optimization outcomes. However, it necessitates substantial support from mathematical and computer technologies.

In practical applications, a combination of these two methods is often employed for optimizing hydraulic machinery performance. Initially, the primary influential factors are determined using the single-factor analysis approach. Subsequently, further optimization is conducted using the multi-parameter optimization method to obtain more refined design solutions.

Multi-objective optimization problems primarily address the simultaneous optimization of multiple numerical objectives within specific contexts. Nevertheless, achieving optimal outcomes for all objectives concurrently poses challenges since improving one sub-objective may result in the degradation of another. Therefore, attaining a balanced optimization state that does not compromise the performance of other objective functions necessitates compromises. This approach effectively facilitates multi-objective optimization.

The multi-objective optimization problem involves a collection of objective functions and their corresponding constraints, which can be expressed mathematically as follows in (1) and (2):

$$F(X) = [f_1(X), f_2(X), \cdots, f_m(X)], \ \ X \in \Omega \subset R^n \tag{1}$$

$$g_i(X) \leqslant 0, \ \ i = 1,2,3\cdots, p \tag{2}$$

where $X = (X_1, X_2, \cdots, X_n)^T$ is an n-dimensional vector in the R^n-space, i.e., the solution range. $f_i(X), i = 1,2,3,\cdots, m$ is the problem sub-objective function, and they conflict with each other, i.e., there is no $X \in \Omega \subset R^n$ such that $[f_1(X), f_2(X), \cdots, f_m(X)]$ obtains the optimal value at X simultaneously. The m-dimensional vector $[f_1(X), f_2(X), \cdots, f_m(X)]$ is located in the space called the target space of the problem. $g_i(X) \leqslant 0, i = 1,2,3\cdots, p$ is the constraint function.

Multi-objective optimization problems are essentially compromise optimization problems, lacking a universally optimal solution. The strategies for handling such problems can be classified into Pareto-frontier-based methods and relative optimal solution methods based on the obtained results. Among these, the Pareto-frontier-based methods offer more comprehensive information about optimal solutions and currently represent the mainstream approach. The compromise optimization solution for multi-objective optimization problems is referred to as the Pareto optimal solution, and the collection of Pareto optimal solutions constitutes the Pareto solution set for the multi-objective optimization problem. In practical applications, the optimal solution(s) from the Pareto solution set can be selected based on the problem's understanding and the decision-makers' preferences [38].

5.4. ISIGHT-Software-Based Optimization Processes and Techniques

The optimization flow chart is shown in Figure 4. The first step in ISIGHT optimization is selecting appropriate optimization parameters, which is crucial for the success of optimization. Optimization parameters are categorized into two types based on the optimization algorithm: global optimization and local optimization. Local optimization parameters mainly consist of the number of iterations and algorithm types, while global optimization parameters include design objectives, constraints, scaling factors, input quantities, and other parameters [39].

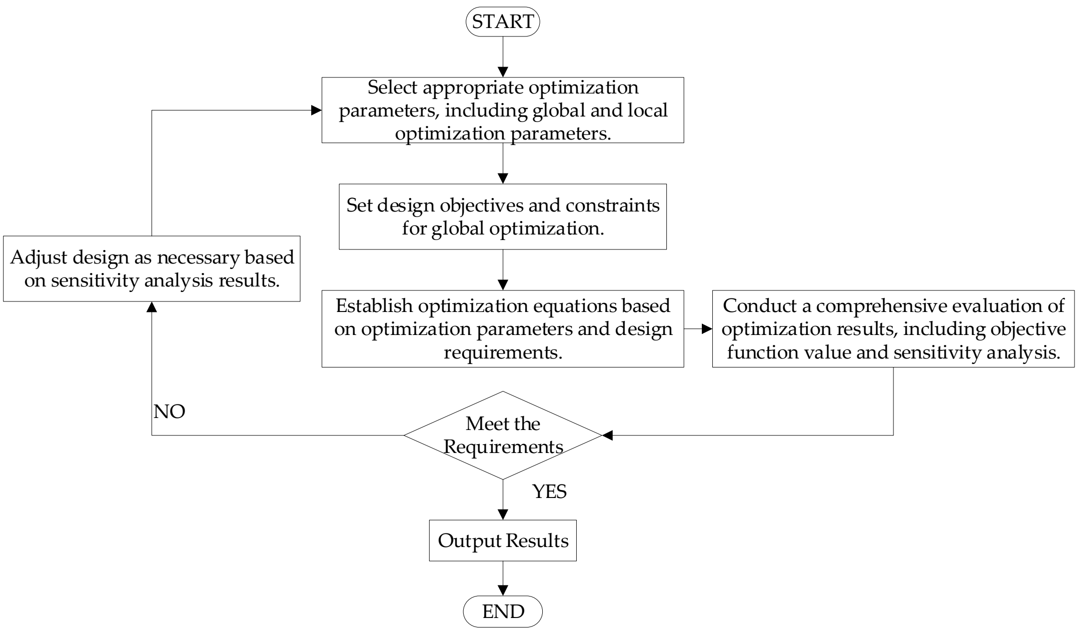


Figure 4. The optimization flow chart.

The number of iterations is an essential local optimization parameter that affects the optimization speed and accuracy. ISIGHT software enables users to set the number of iterations according to their requirements. Typically, a higher number of iterations yields more accurate optimization results, while a lower number results in less accuracy. Algorithm type is also a crucial local optimization parameter that affects the convergence rate of local optimization.

Design objectives establish the direction and purpose of optimization. Different optimization objectives have various impacts on optimization. For example, reducing power consumption or enhancing device efficiency requires relevant goals to be set in the optimization parameters. Constraints are crucial for successfully completing optimization. In ISIGHT, users can set various types of constraints, such as stress limits or operating temperature limits, to ensure that the optimization results meet the design requirements. The scaling factor is a vital global optimization parameter. Users can set the initial value and step size of the scaling factor on ISIGHT software, which can significantly impact the speed and accuracy of the optimization process.

Once the optimization parameters are determined, the next step is to establish optimization equations, taking into account the optimization performance and design requirements.

After completing the optimization process, a comprehensive evaluation of the optimization results is necessary, which should include objective function value and sensitivity analysis. The objective function value reflects the performance of the optimization results. Generally, the smaller the objective function value is, the better the performance of the optimization result is. Sensitivity analysis can help detect the sensitivity of the design parameters to the design objectives and constraints and evaluate the stability and robustness of the optimization results. The results of sensitivity analysis can provide useful information for design adjustment [40].

5.5. Application of ISIGHT Software for Optimizing Hydraulic Machinery

The use of ISIGHT software for studying the optimal design of hydraulic machinery has seen steady growth in recent years. The optimization of hydro-mechanical systems requires the analysis of system performance over time, which may include specific parameters such as pressure, hydraulic efficiency, or head. ISIGHT software is well suited for this type of optimization as it enables users to quickly identify optimal values for specified parameters and evaluate the system's performance under various scenarios.

5.5.1. Optimal Design of Hydraulic Turbines

With rapid advances in science and technology, the optimization design of hydraulic turbines has emerged as a vibrant area of research. ISIGHT, a high-performance visualization and optimization design platform, excels in accomplishing the optimization tasks associated with hydraulic turbines. Numerous scholars have already utilized ISIGHT software to study and analyze the optimal design of hydraulic turbines. These optimized designs offer various benefits, including enhanced hydraulic efficiency, reduced energy consumption, and improved overall performance.

In the field of hydraulic turbine design optimization, several optimization algorithms have been employed in conjunction with ISIGHT software. For instance, Wen et al. successfully applied the non-dominated ranking genetic algorithm to optimize the movable guide vane of a Francis turbine. This algorithm facilitated the exploration of trade-offs among multiple objectives, resulting in improved guide vane performance. The optimization results indicated a significant 10.4% reduction in the total pressure loss in the guide vane flow path and a notable 17.8% increase in the minimum static pressure on the guide vane [41]. Similarly, Ding employed the genetic optimization algorithm to optimize the chord length of a tidal energy turbine's blade, leading to enhanced power coefficients and an expanded operational range [42].

Wen et al. integrated Gambit and ANSYS Fluent 16.0 software with ISIGHT to propose an optimized design method for the crown profile of a low-specific-speed Francis turbine runner. They combined the design of experiments, an approximate model optimization design method, and a particle swarm optimization algorithm to achieve automatic optimization. The results showed that the hydraulic efficiency of the turbine improved by 0.35% after optimization [43]. Hu constructed an approximate model using response surface methodology to establish a relationship between optimization variables and objectives. They employed a multi-objective genetic optimization algorithm within ISIGHT to optimize the approximate model. The optimized design objectives included unit efficiency at the rated pump condition, unit efficiency at the rated turbine condition, unit efficiency at the optimal turbine condition, and cavitation performance of the reversible unit's runner. The final optimization results demonstrated an improvement of 0.33% in the runner pump condition unit-rated efficiency, 2.5% in the turbine condition unit-rated efficiency, 0.17% in the turbine optimal condition efficiency, and approximately 5.17 m in the minimum pressure [44].

These studies exemplify the successful utilization of optimization algorithms in hydraulic turbine design optimization with ISIGHT software. By harnessing these algorithms, researchers and engineers can effectively explore the design space, consider multiple objectives, and achieve significant improvements in hydraulic efficiency and performance. ISIGHT serves as a valuable platform for integrating diverse optimization algorithms, streamlining the optimization design process, and ultimately enabling the development of highly efficient and advanced hydraulic turbine designs.

5.5.2. Pump Design Optimization

Rational and optimized design plays a pivotal role in attaining noteworthy enhancements in pump performance, reducing energy consumption, and extending service life. The utilization of ISIGHT software simplifies the optimization design process, enhancing accuracy, reducing design costs, and improving design efficiency. Consequently, it provides valuable guidance for future advancements in pump development.

Similarly, the application of optimization algorithms has proven effective in pump design optimization. Yang et al. employed the non-dominated ranking genetic algorithm integrated with ISIGHT software to optimize the design parameters of the worm housing section in a mixed flow pump. This algorithm enabled remarkable enhancements in hydraulic efficiency and head, thereby expanding the high-efficiency zone [45]. He utilized ISIGHT software in conjunction with the non-dominated ranking genetic algorithm for the multi-objective optimization of the impeller and worm gear design parameters in a mixed flow pump. The results demonstrated improved hydraulic efficiency, head, and expanded high-efficiency zone. Furthermore, the optimized pump exhibited a more uniform and reasonable static pressure distribution, resulting in reduced energy losses [46].

Zhang employed an integrated design approach within ISIGHT, combining RBF neural network, the non-dominated ranking genetic algorithm, and numerical simulation to optimize the design of a high-pressure pump. This method enabled automatic forecasting of pump performance, resulting in increased weighted average efficiency and improved flow field with reduced energy dissipation. The integration of the RBF neural network and numerical simulation facilitated the accurate modeling and prediction of pump behavior, leading to enhanced design outcomes [47].

Similarly, Fan utilized the multi-island genetic algorithm within ISIGHT software as a tool to optimize the design of LB46 torque converter pump wheel blades. The optimization of LB46 demonstrated overall performance improvements in all cases [48]. Xia et al. developed an optimization platform for axial flow pump impellers based on ISIGHT software, where the multi-island genetic algorithm optimized the calculation process. Following optimization, the hydraulic efficiency of the pump increased, and the efficient region expanded [49]. Lu et al. employed the multi-island genetic algorithm integrated with ISIGHT software to optimize the combination of an impeller and guide vane in an ultra-high specific speed axial flow pump. The optimization resulted in improved efficiency at the design point, while the head remained nearly unchanged [50]. The multi-island genetic algorithm allowed for effective exploration of the design space, leading to enhanced design outcomes.

5.5.3. In the Field of the Optimal Design of Marine Propellers

In the field of marine propeller design, achieving optimal performance poses a significant challenge, requiring meticulous considerations of factors such as feasibility, reliability, maintainability, and overall efficiency. In this pursuit, researchers have turned to ISIGHT software to optimize marine propeller designs. By adjusting key design parameters such as pitch, arch, longitudinal inclination, and chord length, ISIGHT software has proven to be an effective tool for enhancing marine propeller performance.

Cheng et al. employed the design of the experimental method and optimization techniques, combined with approximation methods based on the response surface model, within the ISIGHT multidisciplinary optimization design platform. This novel design engineering framework led to improved propeller efficiency and minimized the pressure coefficient [51]. In another study, Zhao proposed and implemented a new propeller design optimization method utilizing ISIGHT and the vortex lattice procedure SPROP from the lift surface theory. The focus was on investigating the impact of different load chordal distributions on pitch and arch fit. Numerical results demonstrated that the optimized propeller exhibited a uniform load distribution, met thrust and efficiency requirements, and displayed good air bubble priming performance [52]. Liu et al. applied ISIGHT software to integrate analysis modules, including type-value point calculation, model building, meshing, and simulation calculation, to analyze the effects of pitch, arch, longitudinal inclination, and chord length on propeller open water performance. The study revealed that pitch had the most significant impact on propeller open water performance, followed by chord length, arch, and longitudinal inclination. Additionally, the quadratic and interactive terms between factors exerted a more significant effect than longitudinal inclination [53]. Long et al. utilized the ISIGHT optimization platform to optimize the pitch distribution of a propeller, with the objective function being the open water efficiency and minimum pressure coefficient at multiple radii. The study found that optimizing propeller open water performance using a new anti-cavitation profile yielded effective results [54].

In summary, ISIGHT software plays a critical role in the optimal design of hydraulic machinery. Not only does it save significant time and effort for designers, but it also effectively enhances the performance of hydraulic machinery while reducing energy consumption. Therefore, the application of ISIGHT software holds great practical value for the optimal design of hydraulic machinery in today's context.

6. Outlook

Hydro-mechanical optimization in ISIGHT software has emerged as a promising approach for research work. In order to further advance the field of hydro-mechanical optimization, several areas require attention in future research:

(1) It is important to develop a fast and accurate numerical calculation method for hydromechanics in solid-liquid two-phase flow. Currently, numerical simulation models such as the Euler–Lagrange model and Eulerian–Eulerian model are commonly used for the calculation of hydraulic machinery in solid-liquid two-phase flow. By selecting an appropriate numerical simulation model based on the specific fluid motion problems, engineers can quickly and accurately design the best product.

(2) The use of multi-parameter multi-objective optimization methods should be explored to achieve optimal hydro-mechanical system operation performance by considering multiple performance indicators. In addition, the optimization of key mechanical parameters such as impeller speed, blade length, and blade thickness is essential for hydraulic machinery design. While the optimization of hydraulic machinery with single-phase flow as the medium is a more mature area of research, the optimization of hydraulic machinery with solid-liquid two-phase flow media using ISIGHT software requires further attention. Solid media can have a significant impact on the structure

of hydraulic machinery, causing wear, oscillation, and the unstable operation of overflow components.

(3) It is necessary to consider the influence of various parameters of the solid phase, such as density, hardness, and volume, on the characteristics of the flow field in order to effectively optimize the performance of the hydro-mechanical system. By taking into account these factors, researchers can optimize the hydro-mechanical system's performance in a comprehensive manner. In summary, continued efforts in these research directions will help advance the field of hydro-mechanical optimization in ISIGHT software, leading to the development of more efficient and reliable hydraulic machinery designs.

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