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Research on Application of Scale Loading Technology in Large Hub Body Model

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Abstract **Review Article**

With the rapid development of science and technology, the demand for research on loading performance and structural strength of large and complex systems is increasing. The propeller hub body is the core component of the ship's controllable pitch propeller device. In order to study the fatigue life and stress of large and compact hubs, considering the constraints of cost and test conditions, the propeller hub body in the high-power hub assembly is taken as an example to introduce the scaled loading technology simulation test and carry out relevant research. In the early stage of the test, by summarizing the practical application of scaled loading technology in various fields and the scaled ratio and parameter relationship values used in the design of scaled models, the scaled values and parameter values required for the propeller hub body design are analyzed. By using finite element simulation, the maximum stress distribution of the bearing stress area in the scaled hub body prototype and the positive prototype under different working conditions is compared. The results of the stress distribution cloud map of the key area of the propeller hub body show that within a certain range, the propeller hub body scaled prototype has a high accuracy in simulating the structure and material behavior. This study proves the feasibility and scientific validity of the application research of scaled loading technology in large hub assemblies.

Keywords: Hub Body, Fatigue Life, Scaled Loading Technology, Finite Element Simulation.

1. INTRODUCTION

High-power compact paddle hub assembly is an indispensable key component in modern engineering, which is widely used in ship propulsion, wind power generation, aerospace and other fields. In the marine propulsion system, the paddle hub assembly is an important component connecting the marine engine an-d propeller. With the continuous advancement of technology and increasing demand, its performance and reliability play a vital role in the performance and safety of the entire largescale machinery. High-power compact propeller hub assemblies are required to withstand complex loading conditions in actual operation, including static, dynamic and environmental loads. In the process of studying the mechanical proper types of large and complex structural components, such as ships, reliable prediction of structural properties at the initial stage is particularly important in order to prevent cost losses that may be triggered by the measured parameters at a later stage. As an important means to obtain the mechanical properties of complex structures, static loading tests provide objective and direct data. However, due to the size and complexity of very large equipment, full-scale modeling tests often face numerous limitations, which may lead to economic and time wastage. Therefore, it is particularly important to select an appropriate test method. The scaled loading technique can simulate the mechanical behavior of the actual structure under various loading conditions by fabricating and testing a scaled model, which provides a bas-is for the design of the original mod-el. Yu Nan *et al.*, [1], scaled down the real ship according to the scaled-down ratio of 1:100, studied the relationship between the influencing fac-tors of hull surface potential distribution through the scaled-down model, and established the hull applied current cathodic protection system. Cai Mingjuan *et al.*, [2], elaborated and summarized the whole process of s-hip downsizing principle model and electromagnetic compatibility test. Using Maxwell's equations, the shrinkage coefficient relationship is det-ermined, in which the ship model shrink-age is n, the wire size length shrink-age ratio is $1/n$, the shrinkage ratio of frequency and conductivity is n, and other parameters are unchanged. Gong Junjun *et al.*, [3], people proposed a new program based on the similarity theory can be carried out in the study of ship guns and other weapons. According to the 1:2scaled length ratio design of the guncarrier experimental model, and the use of magnitude analysis, equation analysis and finite element method, the original gun carrier and scaled model of the vibration characteristics of the nearest similarity between the expression, and through the AN-SYS finite element method of computational analysis and experimental comparisons to verify the accuracy of the similarity of the relationship. Zhou Lingbo *et al*., [4], in the case of the ship design in the support dyna- mics of the impact, according to the dynamic parameters of the scaling conversion method, according to the1:4 scaling ratio to calculate the scaling ratio of the design of the shaft system and the real ship propulsion shaft system of the design of the quality of the mass, bearing load, bearing strength, transverse vibration modal frequency and acceleration transfer function of a series of dyna-mics simulation analysis and comparative analysis, and ultimately get the structural mass compared with the real ship shaft system of the lar-gest. The maximum difference in structural quality is 1.10%, the maxi-mum difference in bearing load quality is 2.12%, and the bearing supp-ort stiffness is within a reasonable range compared with the real ship's shaft system. From the above research, it is easy to find that the scaled loading technology is widely used in the field of ships and has feasible basis. This paper takes the paddle hu-b body in the high-power paddle hu-b assembly as an example to carry out relevant research. The principle of scaled loading technology is used to determine the scaling ratio of the paddle hub body assembly, and the maximum stress distribution in the key areas of the scaled paddle hub body and the positive prototype paddle hub body is analyzed to explore the application of the scaled loading technology in the high-power paddle hub assembly.

2. Hub Body Scaling Component Design

2.1 Scaled Loading Theory

The core idea of the scaled loa-ding technique is to construct a scale down model to simulate the behavior of the actual structure in a controlled test environment, so as to effectively predict and evaluate its performance under various working conditions. This technique is widely u-sed in the research of ships and other ultra large equipment, which can avoid the cost and time wastage of full-size tests. The scaled loading theory is based on the similarity theory, which is mainly used to determine the similarity relation-ship between the model and the prototype to ensure that the tests conducted in the scaled model can truly reflect the characteristics of the original model. The similarity theory includes three basic theorems:

1). Similarity First Theorem

Similar phenomena can be described by exactly the same set of equations, while, in the equations, all physical quantities are proportional to each other in corresponding time and position.

2). Second Theorem of Similarity

For a given physical phenomenon, if there are a system of equations with p variables and q equations, w-here the m variables are independent and uncorrelated in terms of their magnitudes, and the q-m variables are derived magnitudes. After trans-formation by means of the similarity theorem, these quantities can be re-presented by a function consisting of a dimensionless similarity criterion. This theorem permits the derivtion of the similarity criterion using the relevant physical quantities without specifying the specific Mathema-tical equations.

3). Similarity Third Theorem

Also known as the Inverse Theo-rem of Similarity, it focuses on the sufficient conditions for similarity between two phenomena, i.e., if two phenomena are described by the same relational equation, while their single-valued conditions are similar, and at the same time the values of t-he bases for similarity judgments consisting of these single-valued conditions are equal, then the two phenomena can be said to be similar.

Secondly, model design is one of the key steps in the scaled loading technique, which needs to be considered in the design process includeing geometric similarity, physical property similarity and similarity of loading conditions. And the establishment of the similarity relationship needs to be carried out through t-he methods of magnitude analysis, equation analysis or matrix method. These three methods are also know-n as similarity criterion derivation methods. Among them, the most widely used is the method of magnitude analysis.

1). Calculus of Equations

The nature and laws of physical phenomena are revealed primarily through the establishment of mathematical equations describing the behavior of a physical process or system. First, the physical background of the research problem is determined, and those physical quantities and their interrelationships are identified, and then the equations are established according to the laws and principles of physics; secondly, the similarity constants are determined, which in turn respond to the proportionality between different variables. Next, replace the physical quantities in the equations with similar costants to obtain similarity index equations. Finally, the actual results are compared to verify the reliability of the equations.

2). Quantile Analysis (Physics)

Also known as causal analysis, t-he core of the method is to analyze and determine the relationship bet-ween physical phenomena or physical processes by means of the magnitudes of the physical quantities. W-hen using the method of quantum analysis, it is necessary to ensure that each quantum is independent, and through the dimension lessness of the p variables in the equation, you can get the function of $p-m$ independent dimensionless parameters $x_1, x_2, \ldots, x_n$. Thus, it reveals the intrinsic connection of physical quantities after dimensionless quantification. It enables similar analyses to be carried out without mastering the specific mathematical equations of the phenomenon.

3). Matrix Method

The matrix method uses a matrix of measures to derive a similarity criterion and belongs to a form of measure analysis.

2.2 Dimensioning of Pad-Dle Hub Body Reducti-On Ratio

Through the application of the scaled loading technique in various fields [5-22], it can be found that the similarity triple theorem is the theoretical basis of the similarity theorem, and there are usually three methods for the derivation of the similarity criterion: theorem analysis method, equation analysis method and magnitude analysis method. Combining these three methods and the influence of equivalent structural stress o-n eliminating the size effect, the shrinkage relationship between the shrinkage model and the prototype physical quantities as well as the similarity criterion of equivalent life are derived. The following table is shown:

Table 1: Scaling relationship between physical quantities of scale model and prototype

physical quantity	scale of reduction
geometric dimension *I*	K_D
modulus of elasticity *E*	K_E
Material density ρ	K_ρ
mass *M*	$K\rho KI^3$
rotational inertia *J*	$K\rho KI^5$
support stiffness *K*	*KI KE*
the magnitude of the excitation force *F*	KI^2 *KE*
frequency ω_n acceleration response *a*	$K_I^{-1}\left(K_E/K_\rho\right)^{1/2}$ *KE/KIKρ*
acceleration transfer function *H*	$KI^3K\rho$

Table 2: Equivalent Life Similarity Criteria

similarity criteria	relationship between physical quantities
Π_1	$E^{-1}l^{-2}Q$ (*Q* applied force)
Π_2	$E^{-1}l^{-3}Z$ (Z-torque)
Π_3	$E^{-1/2}\rho^{1/2}la$
Π_4	$E^{-3/2}\rho^{-1/2}\lambda TG$
Π_6	μ (material Poisson's ratio)
Π_7	*S* (model failure rate)
Π_8	L_S (model life)
Π_9	$E^{1/2}\rho^{-1/2}l^{-1}t$ (*t* test time)

where λ mean material thermal conductivity, *TG* mean temperature gradient. According to the similarity criterion Π_9, the overall time of the model test can be inferred, and according to Π_6, Π_7 and Π_8, it can be inf-erred that the dimensionless quantities of the model need to be consistent with the original model. In addition, according to Π_1, Π_2, Π_3 and Π_4, it should be ensured that the actual working conditions of loading satisfy the similar conditions of kinematics and thermodynamics when performing the equivalent life model tests. In the design of the scaled parts of the paddle hub body, it needs to be able to reflect the basic physical phenomena as well as its basic dimensions to fulfill the requirements of the laboratory equipment installation. In addition, these two requirements are ensured while keeping its design as simple as possible. We have used the similarity criterion to determine the conditions that the corresponding physical quantities need to satisfy in the experiment as well as the scaling relationship. Considering all the influencing factors, the basic scale values (e.g., length, diameter) of the scaled component are s-et at ratio of 1:4, and a structural material similar to that of the full-size propulsion shaft system is selected to ensure that its density and elastic modulus are close; the load scaling value is set at 1:8.

3. An Investigation of the Application of Scaled Loading Tech-Nique in Paddle Hubbody

The paddle hub body is the key component in the paddle hub assembly, carrying the transmission of propulsive power while effectively supporting and distributing the load of the paddle blades. Due to the limited space inside the hub body, it is necessary to reasonably layout and accommodate the complex pitch mechanism for controlling the angle of the paddle blades, so as to regulate the propulsive power and adapt t-o different working conditions. The stress distribution of the upper and lower bearing surfaces of the bearing and the inner bearing surface of the paddle hub is the most prone to stress concentration and deformation for the paddle hub, so this paper takes the paddle hub as the object of study, and carries out the finite element simulation on the positive proto type model and the scaled-down prototype model of the paddle hub, extracts the stress distribution of the scaled-down model of the paddle hub and the positive prototype und-er various working conditions, and compares the results of stressing of both of them under different working conditions, and draws relevant conclusions. The stress distribution of the scaled-down model of the hubbody and the positive prototype are extracted respectively under each working condition, and the stress results of the two models under different working conditions are compared to draw relevant conclusions. The geometry of the paddle hub is evenly divided into five equal parts (as shown in Fig. 1), and the finite element mesh is divided by Hyper Mesh software. The bearing ring is divided into hexahedral mesh, and the remaining part is mainly divided into tetrahedral mesh (as shown in Fig. 2).

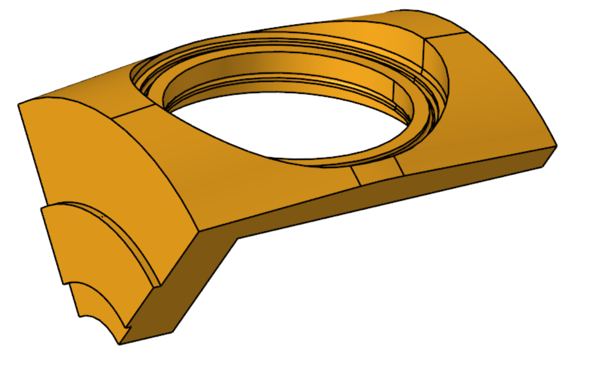

Figure 1: Geometry diagram of propeller hub body

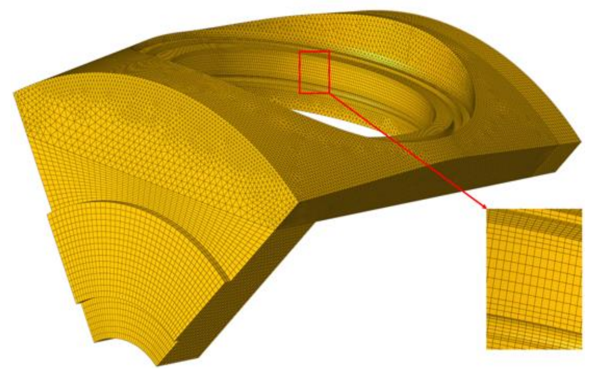

Figure 2: Grid diagram of propeller hub body

For the stress areas of focus for the paddle hub body, they are numbered according to the diagram below (e.g., Fig. 3). Area 1 is the inside of the paddle hub body bearing ring, a-rea 2 is the upper surface of the paddle hub body bearing, area 3 is the radial inner groove of the paddle hu-b body bearing ring, and area 4 is t- he bottom of the paddle hub body b-earing ring.

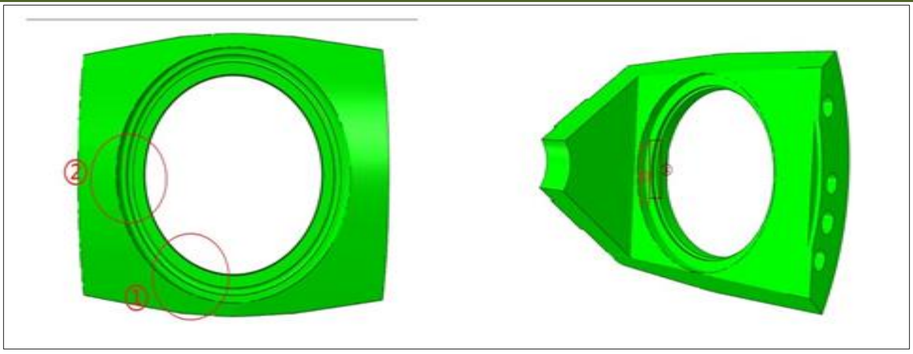

Figure 3: Schematic diagram of propeller hub body

In order to investigate the four regions of the scaled-down proto type and the positive prototype of the paddle hub body, the stress distribution in these four regions is calculated separately, and the stress cloud diagrams of the four regions are plotted as shown below.

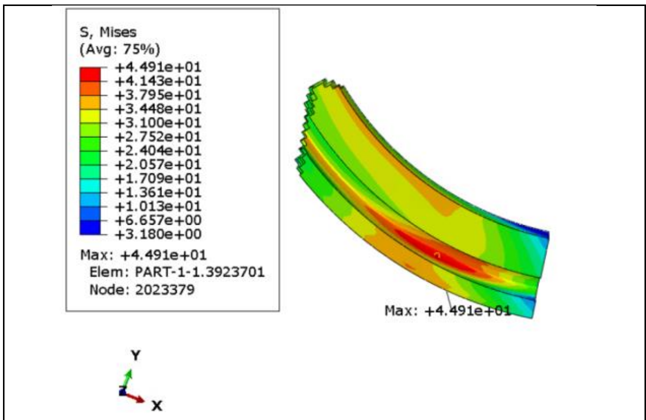

Figure 4: Stress nephogram of scale prototype area 1

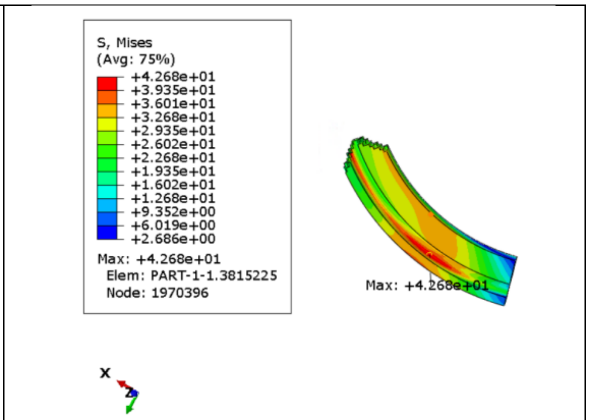

Figure 5: Stress nephogram of prototype area 1

In region 1, the maximum stress in the scaled-down prototype is 44.91 MPa and the maximum stress in t-he positive prototype region is 42.68 MPa.

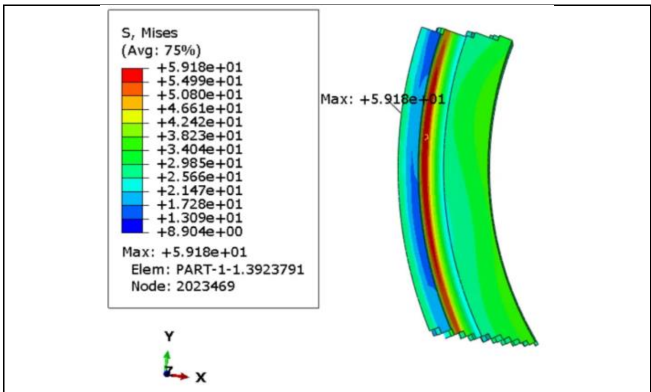

Figure 6: Stress nephogram of scale prototype area 2

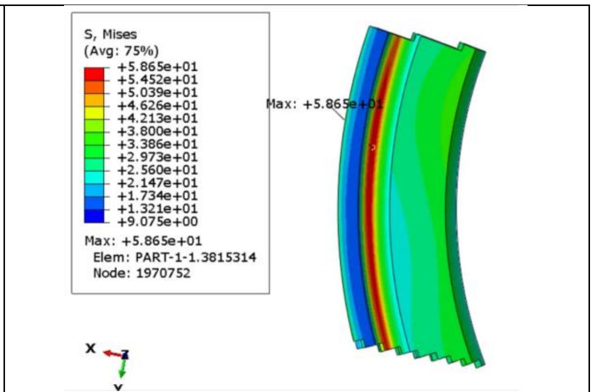

Figure 7: Stress nephogram of prototype area 2

In region 2, the maximum stress is 59.18 MPa for the scaled-down prototype and 58.65 MPa for the positive prototype.

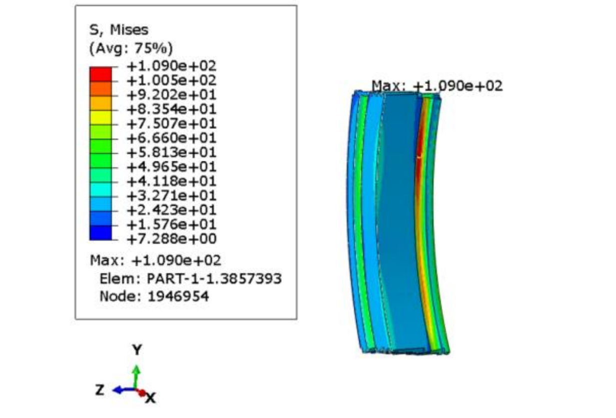

Figure 8: Stress nephogram of scale prototype area 3

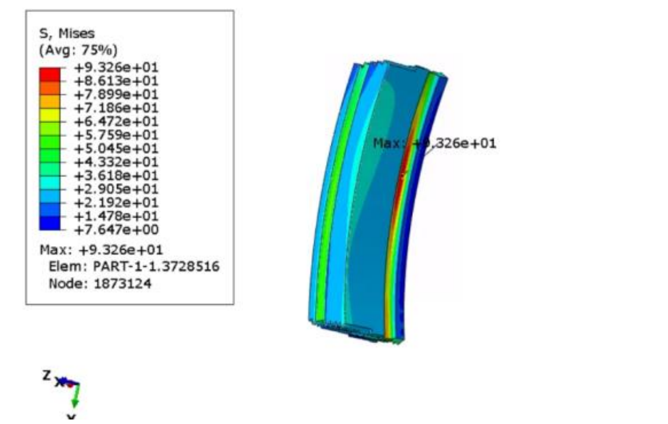

Figure 9: Stress nephogram of prototype area 3

In region 3, the maximum stress in the scaled-down prototype is 109 MPa and the maximum stress in the positive prototype is 93.26 MPa.

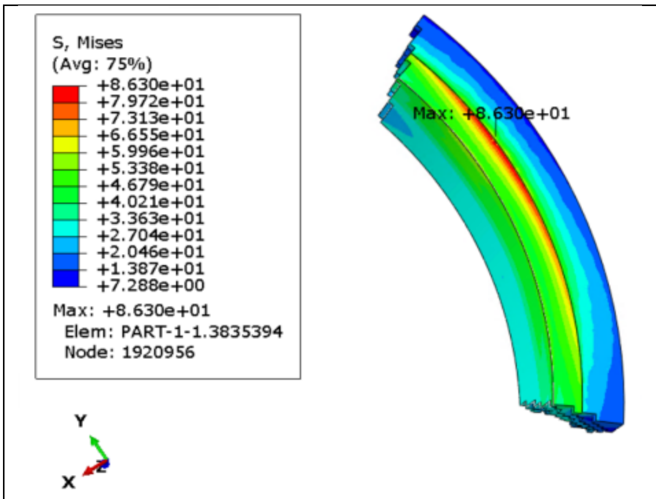

Figure 10: Stress nephogram of scale prototype area 4

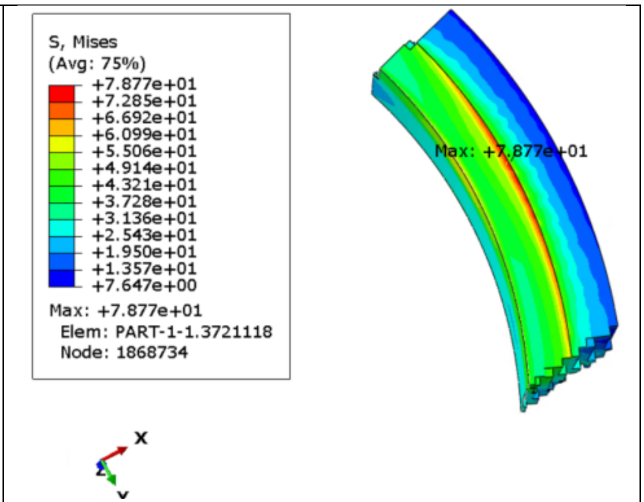

Figure 11: Stress nephogram of prototype area 4

In region 4, the maximum stress of the scaled-down prototype is 86.3 MPa and the maximum stress of the positive prototype is 78.77 MPa. Th-e comparison of the maximum stress results of the scaled-down and positive prototypes in these four regions is shown in the table below.

Table 3: Comparison Table of Maximum Stress Value between Scale Prototype and Normal Prototype of propeller hub body

hub body region	maximum stress of scale prototype	Maximum stress of normal prototype
region 1	44.91	42.68
region 2	59.18	58.65
region 3	109	93.26
region 4	86.30	78.77

Table 4: Comparison Table of Maximum Stress Value between Scale Prototype and Normal Prototype of propeller hub body

hub body region	difference (Mpa)	spread (%)
region 1	2.23	5.22%
region 2	0.53	0.90%
region 3	15.74	16.88%
region 4	7.53	9.56%

Generally speaking, the difference between the scaled-down prototype and the positive prototype in the same area is within 20%, which means that the scaled-down prototypecan meet the test requirements. According to the data in the table, the maximum stress values of the scale-d-down prototype and the positive prototype of the paddle hub body s-how a high degree of similarity in several regions, especially in region 2, where the maximum stress difference is only 0.53 Mpa, which indicates that the scaled-down prototype isable to accurately simulate the stress distribution of the positive proto-type in most of the regions, which verifies the scientific and applicability of the scaled-down modeling. However, the stress differrence in region 3 is larger, reaching 15.74Mpa, but the differences in all regions are within the acceptable range. The str-ess difference value in region 3 also shows that there is not exactly similar phenomenon in the scaled loading test. If this region needs to ensure that the regional difference value is within 10%, the design and material selection of this part can be further optimized and designed. The comprehensive stress distribution cloud diagrams of the focused regions of the paddle hub body can be concluded that the scaled-down prototype of t-he paddle hub body has a high accuracy in the simulation of structureal and material behaviors within acertain error range.

4. CONCLUSION

In this study, the feasibility of ap- plying the scaled-down loading technology in large paddle hub body is explored through systematic analysis and experimental verifycation. By selecting reasonable scaling ratios and parameter relationship values, and comparing and analyzing the b-earing stress distribution between t-he scaled-down prototype and the positive prototype under different working conditions, the results show that the two have a high degree of consistency in the area of the maxi-mum stress distribution, and the stress difference is within the accept-able error range. This shows that the scaled loading technique can effectively simulate the stress distribute-on of large paddle hubs, which verifies the scientific and effective nature of the scaled loading technique in t-he modeling of large paddle hubs. This study provides reliable theoretical support and practical basis for t-he design of large and complex structures, and proves the potential and application value of the scaled loading technique in reducing the experimental cost and shortening the RD cycle. Meanwhile, this study also provides a strong reference for further optimizing the design of the scaled model to improve the simulation ac-curacy in the future.

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